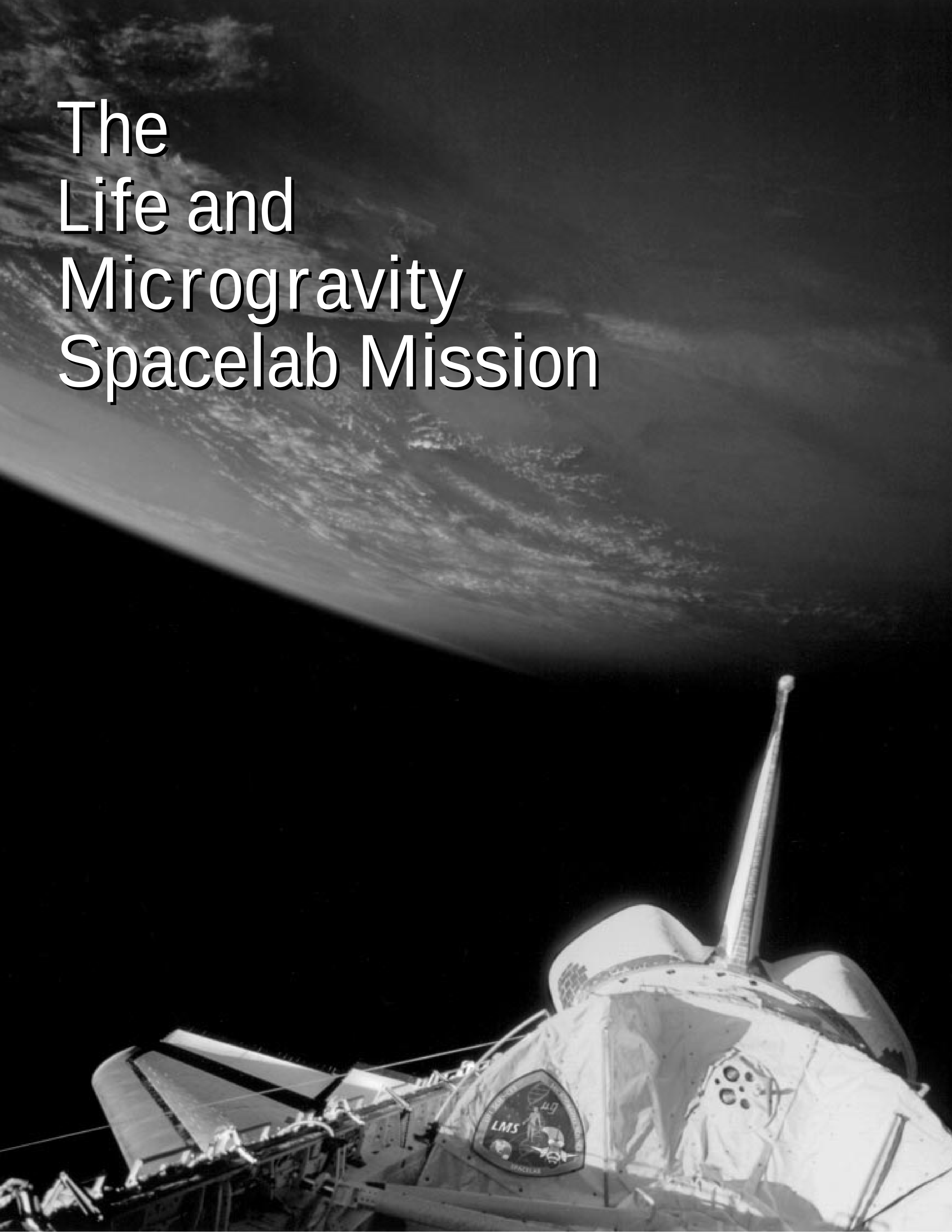
The Life and Microgravity Spacelab Mission



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Life & Microgravity Spacelab Mission

Table of Contents

Additional information about the LMS mission
is available on the World Wide Web at the following address:
http://liftoff.msfc.nasa.gov/spacelab/lms

The Life and Microgravity Spacelab Mission

Orbiting Planet Earth, astronauts and scientists work together to perform scientific investigations in a unique laboratory called Spacelab, which is carried in the Space Shuttle's payload bay. This short-term, Shuttle-based research will set the stage for long-term science in a permanent space station near the turn of the century. Interaction between investigators on the ground and crewmembers conducting experiments in Spacelab allows the scientists on Earth to work virtually side-by-side with their colleagues in space.

Science in the Shuttle and Spacelab has become a cooperative international effort as investigators around the world collaborate in experiment development, mission operation, and data analysis. This sharing of knowledge and resources across political and geographic boundaries benefits all of Earth's inhabitants, as the information gained about the chemistry and physics of matter and about the natural laws that govern our existence allows us to improve our quality of life both at home on Earth and in new habitats in space.

The Life and Microgravity Spacelab (LMS) mission is an international endeavor managed by the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC). Building on a history of successful spaceflight, the LMS mission exemplifies the successful communication and cooperation that have been established both on an international level among space agencies and also among the various NASA centers and participating research institutions. Representing a convergence of the Spacelab Life Sciences and the International Microgravity Laboratory programs, LMS will fly aboard the Space Shuttle Columbia *in the summer of 1996 with an international crew of 7 for a planned 16-day mission devoted to the study of life and microgravity sciences.*


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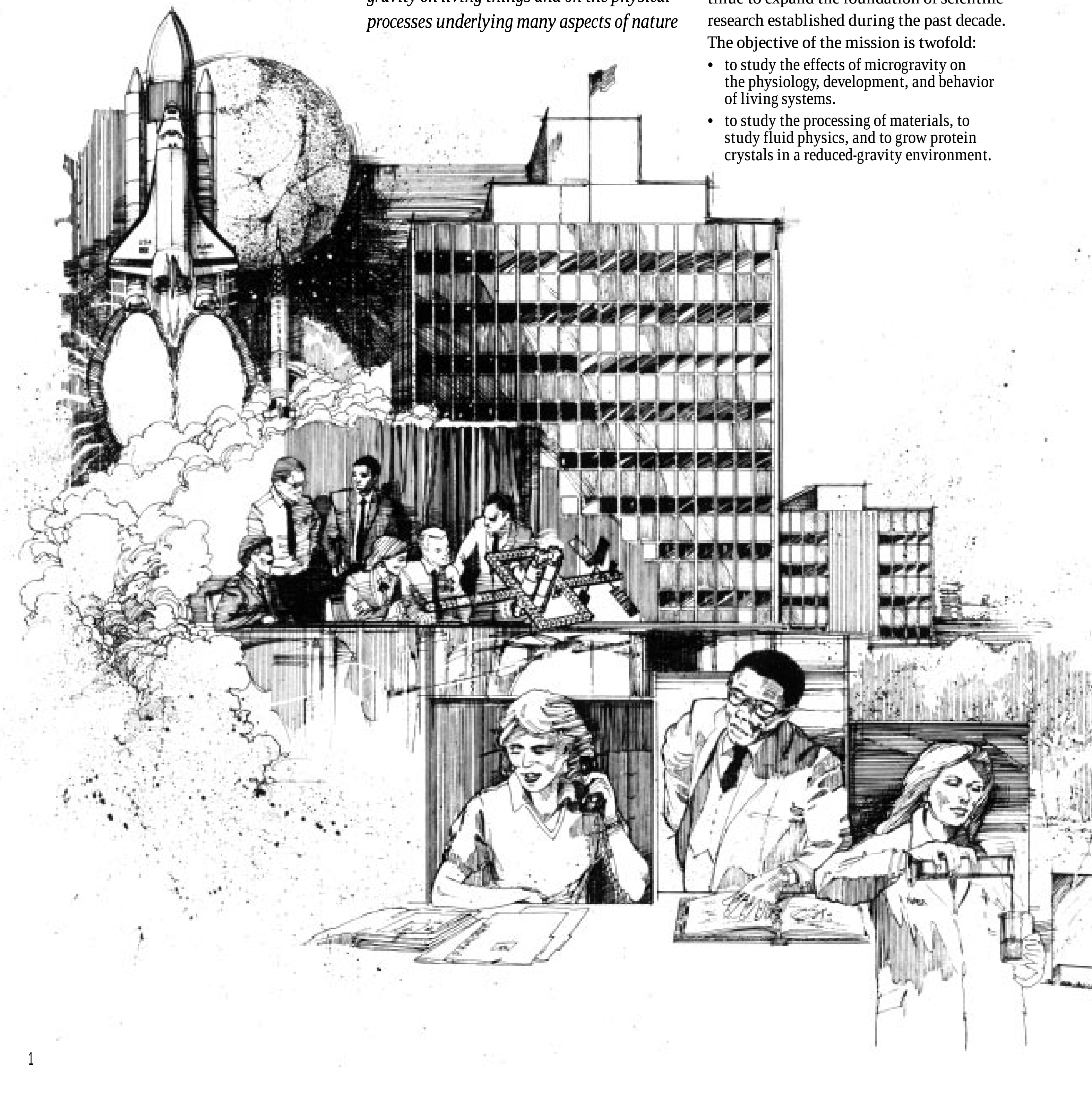
Since early in the 1980s, the platform provided by the combined Space Shuttle and Spacelab has provided the opportunity for scientists from many nations to conduct scientific research in space. This orbiting laboratory provides an environment similar to laboratory conditions on Earth with one notable exception: the effect of gravity. As the orbiter moves around Earth at a speed of 17,500 miles (28,000 kilometers) per hour, it is in a state of freefall, which results in near weightlessness, or microgravity. This singular characteristic gives us a glimpse into the influence of gravity on living things and on the physical processes underlying many aspects of nature and technology. It also gives rise to questions about our ability to sustain life for prolonged periods in space and about the subtle mechanisms involved in materials processing that are obscured by Earth's gravity.

The LMS mission will seek answers to some of these questions and will build on and continue to expand the foundation of scientific research established during the past decade. The objective of the mission is twofold:

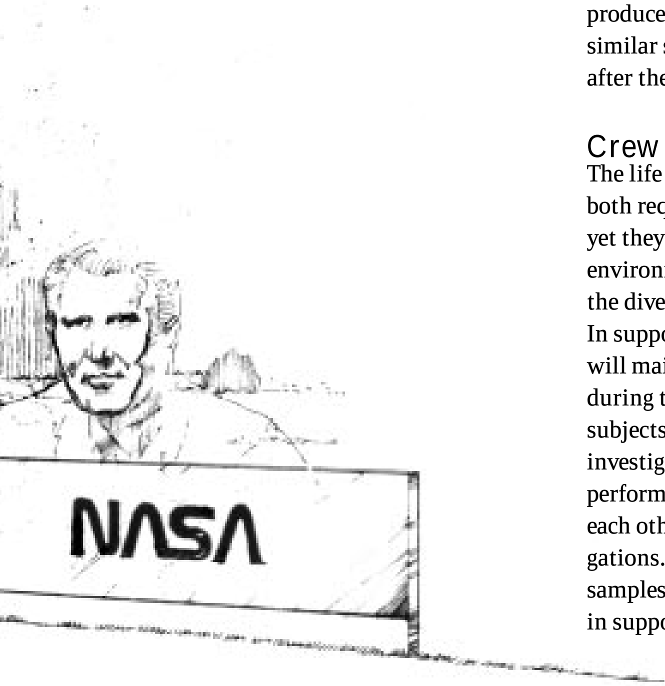
- to study the effects of microgravity on the physiology, development, and behavior of living systems.
- to study the processing of materials, to study fluid physics, and to grow protein crystals in a reduced-gravity environment.



Life Sciences

A broad range of human physiology experiments will be conducted during the mission. These investigations include specific studies on bone tissue loss, muscle performance and adaptation, caloric intake and energy expenditure, pulmonary function, neurovestibular adjustment and behavior, and general studies on the effects of spaceflight on human performance and on daily sleep and biological (circadian) rhythms. Physiological data gathered from each astronaut during the 3 months before flight will provide a baseline with which flight data will be compared. During the mission, investigators will assess both the short-term and long-term effects of the microgravity environment and the adaptive reactions of the astronauts. Postflight testing will assess the body's readjustment to Earth's gravity.

Life scientists also will collect data on the adaptation of other living systems to the microgravity environment. Experiments include studies on the development of the neural system in fish eggs, alterations in the metabolism of bone in rats, and changes in the cell structure of conifer seedlings. All of these experiments complement each other to provide a comprehensive view of the effects of gravity and the stresses of spaceflight on biological systems.



Microgravity Science

The microgravity environment of Spacelab provides the opportunity to explore new phenomena and to test basic theories. In a space laboratory, physical processes can be observed from a unique perspective in an environment in which gravity is not dominant, as it is on Earth. In ground laboratories, gravity-related processes such as buoyancy and sedimentation can control materials and fluid processes and can restrict the parameters studied. In microgravity, the effects of gravity-driven phenomena are almost eliminated, making it easier to examine aspects of these processes that are difficult to study on Earth. Investigators also will be able to study fluid processes that are masked or distorted on Earth, such as motions generated by temperature variations along the surface of liquid/air or liquid/liquid boundaries (thermocapillary flows) and the shift from one state of matter to another (phase transitions). Advancing our knowledge of many natural phenomena and technological processes depends on an understanding of these basic mechanisms, and this knowledge may help us develop the next generation of materials needed for high-tech applications.

Scientists will produce metallic alloys and protein crystals, study fluid behavior, and examine how surface-tension forces, thermal gradients, and other parameters affect materials processing and fluid behavior in microgravity. The inflight microgravity environment will be characterized, and samples produced in space will be compared with similar samples made on Earth before and after the flight.

Crew Activities

The life and microgravity science programs both require a near-gravity-free environment, yet they study different influences of this environment. The activities of the crew reflect the diverse nature of these investigations. In support of the life science goals, the crew will maintain normal daily cycles, sleeping during the same 8-hour period. They will be subjects and researchers for the life sciences investigations, gathering samples and performing measurements on themselves and each other for the human physiology investigations. In addition, the crew will change out samples and film and perform other activities in support of the microgravity experiments.

An International Endeavor

The LMS mission is a demonstration of the cooperative effort required to ensure efficiency and effectiveness as space exploration increasingly becomes an international endeavor. Using the Space Shuttle, designed by NASA, and Spacelab, designed and built by the European Space Agency (ESA), LMS is truly an international mission. Investigators and hardware developers are from the United States, Switzerland, Sweden, Austria, Germany, Belgium, The Netherlands, Canada, Italy, and France. They represent NASA, ESA, and the Canadian (CSA), Italian (ASI), and French (CNES) Space Agencies. The LMS crew further demonstrates the international nature of the mission: the flight crewmembers are from the United States, Canada, and France, and alternate crewmembers are from Spain and Italy. During the mission, members of the investigative teams will conduct ground studies, monitor experiments, and receive data at remote sites throughout the United States and in Belgium, France, and Italy. This intercontinental effort exemplifies the broad international partnerships and scientific alliances that are necessary to maintain a strong space program in the future.

LMS Mission Management

The Life and Microgravity Spacelab mission is the culmination of extensive efforts by an international team of scientists, engineers, and support personnel. Utilizing the experience and cooperative relationships that have been developed over a decade of space research, these individuals are involved in the planning, design, development, integration, testing, and operation of the many systems that are required to accomplish the science objectives of the LMS mission.

Marshall Space Flight Center is the lead center responsible for the LMS science payload. MSFC provides the Mission Manager, the Mission Scientist, the Spacelab Mission Operations Control Center, the Payload Operations Control Center, and the engineering expertise required to integrate the experiment equipment into a payload complement that will successfully accomplish the mission's scientific objectives while ensuring the safety of the crew and the integrity of the vehicle.

LIFE SCIENCES

NASA'S Life Sciences Program Goals

- To utilize the unique space environment to enhance our understanding of fundamental gravity-dependent biological processes
- To use this knowledge to develop the scientific and technological foundations for supporting humans in space
- To apply this knowledge and technology to improve our competitiveness, education, and quality of life on Earth

Additional information about the LMS mission is available on the World Wide Web at the following address:

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LIFE SCIENCES EXPERIMENT COMPLEMENT

The Life Sciences experiments are grouped according to discipline.

HUMAN PHYSIOLOGY DISCIPLINE

JSC Project, NASA/Johnson Space Center, Houston, Texas

Musculoskeletal Experiments

- *Effects of Weightlessness on Human Single Muscle Fiber Function*
- *Relationship of Long-Term Electromyographic Activity and Hormonal Function to Muscle Atrophy and Performance*
- *The Effects of Microgravity on Skeletal Muscle Contractile Properties*
- *Effects of Microgravity on the Biomechanical and Bioenergetic Characteristics of Human Skeletal Muscle*
- *Magnetic Resonance Imaging After Exposure to Microgravity*
- *An Approach to Counteract Impairment of Musculo-Skeletal Function in Space*

Metabolic Experiments

- *Direct Measurement of the Initial Bone Response to Spaceflight*
- *Measurement of Energy Expenditure During Spaceflight with the Doubly Labeled Water (DLW) Method*

Pulmonary Experiment

- *Pulmonary Function in Weightlessness*

Human Behavior and Performance Experiments

- *Human Sleep, Circadian Rhythms, and Performance in Space (SACS)*
- *Microgravity Effects on Standardized Cognitive Performance Measures (PAWS)*

Neuroscience Experiments

- *Torso Rotation Experiment (TRE)*
- *Canal and Otolith Integration Studies (COIS)*

Bedrest Study, NASA/Ames Research Center, Moffett Field, California

SPACE BIOLOGY DISCIPLINE

- *Role of Corticosteroids in Bone Loss During Spaceflight, NASA/Ames Research Center, Moffett Field, California*
- *Development of the Fish Medaka in Microgravity, NASA/Ames Research Center, Moffett Field, California*
- *Lignin Formation and the Effects of Microgravity: A New Approach, NASA/Kennedy Space Center, Cape Canaveral, Florida*

MICROGRAVITY SCIENCE

NASA'S Microgravity Science Program Goals

- To define and conduct a broadly based Microgravity Science and Applications Research Program in the physical and chemical sciences and in biotechnology
- To support and foster the development of suitable flight instrumentation
- To foster the growth of an interdisciplinary research community, united by shared goals and resources to conduct research in the space environment
- To promote the United States' industrial involvement and investment in the applications of space research for the development of new, commercially viable products, services, and markets resulting from research in the space environment
- To utilize future space station capabilities together with other carriers, such as free-flying platforms and extended-duration orbiters, to provide the optimum experiment/carrier combination for maximizing science return
- To provide for international cooperation and coordination in conducting space-related basic and applied research

MICROGRAVITY SCIENCE EXPERIMENT COMPLEMENT

The Microgravity Science experiments are grouped according to facility.

BUBBLE, DROP, AND PARTICLE UNIT (BDPU), ESA

- *Bubbles and Drops Interaction with Solidification Fronts*
- *Evaporation and Condensation Kinetics at a Liquid Vapor Interface*
- *The Electrohydrodynamics of Liquid Bridges*
- *Nonlinear Surface Tension Driven Bubble Migration*
- *Oscillatory Marangoni Instability*
- *Thermocapillary Migration and Interactions of Bubbles and Drops*

ACCELEROMETERS

- *Microgravity Measurement Assembly (MMA), ESA*
- *Orbital Acceleration Research Experiment (OARE), NASA/Lewis Research Center, Cleveland, Ohio*
- *Space Acceleration Measurement System (SAMS), NASA/Lewis Research Center, Cleveland, Ohio*

ADVANCED GRADIENT HEATING FACILITY (AGHF), ESA

- *Comparative Study of Cells and Dendrites During Directional Solidification of a Binary Aluminum Alloy at 1-g and Under Microgravity*
- *Coupled Growth in Hypermonotectics*
- *Effects of Convection on Interface Curvature During Growth of Concentrated Ternary Compounds*
- *Equiaxed Solidification of Aluminum Alloy*
- *Interactive Response of Advancing Phase Boundaries to Particles*
- *Particle Engulfment and Pushing by Solidifying Interfaces*

ADVANCED PROTEIN CRYSTALLIZATION FACILITY (APCF), ESA

- *Crystallization of EGFR-EGF*
- *Crystallization of Crustacyanin Subunits*
- *Crystallization of Engineered 5S rRNA Molecules*
- *Crystallization of Thermus Thermophilus AspRS*
- *Monitoring of Lysozyme Protein Crystal Growth Process in Microgravity via a Mach-Zehnder Interferometer and Comparison with Earth Control Data*
- *Crystallization of the Nucleosome Core Particle in Space*
- *Enhanced Resolution Through Improved Crystal Quality in the Crystal Structure Analysis of Photosystem I*
- *Mechanism of Membrane Protein Crystal Growth: Bacteriorhodopsin — Mixed Micelle Packing at the Consolution Boundary, Stabilized in Microgravity*
- *Crystallization in a Microgravity Environment on CcdB, a Protein Involved in the Control of Cell Death*
- *Crystallization of Sulfolobus Solfataricus Alcohol Dehydrogenase*
- *Growth of Lysozyme Crystals at Low Nucleation Density*
- *Advanced Protein Crystallization Facility on the Life and Microgravity Sciences Mission*

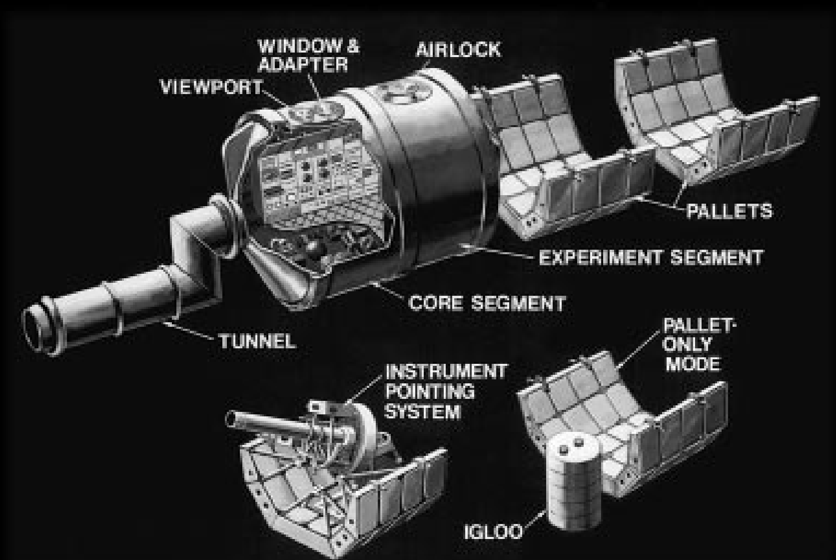
WHAT IS SPACELAB?

Spacelab, the product of an extremely successful international partnership between NASA and the European Space Agency, is a series of modular components that can be assembled into unique mission configurations for flight on the Space Shuttle. The components consist of pressurized laboratory sections, pallets, and associated hardware.

Pressurized Spacelab modules provide a shirtsleeve environment for conducting research. These laboratories come in two basic module configurations: long or short. The short module can be used for a small number of experiments or in conjunction with experiments mounted on pallets in the Shuttle payload bay. The long module is used for a large number of experiments. Both modules have similar basic equipment, such as a general-purpose workstation and master controls. They also can be outfitted with a variety of equipment needed on a particular mission, including modified standard medical tools, multipurpose reusable mini-labs, and plant and animal habitats for life science experiments, along with lockers, furnaces, and various facilities for physical science research. The hardware and facilities may be controlled or monitored by the Shuttle's crew, commanded by investigators on the ground, or operated autonomously by pre-programmed computer control.

The Life and Microgravity Spacelab is a long module that holds eight double racks and four single racks of equipment, which contain the workstations, experiment facilities, furnace, freezers, storage compartments, and support equipment needed for a majority of the experiments. Other hardware is located in the aisle of the Spacelab and in the Shuttle middeck.

The European Space Agency (a consortium of 14 European countries sponsoring space research and technology) funded, developed, and constructed Spacelab. NASA is responsible for its launching and operational use. The LMS mission continues this successful partnership with its international cadre of investigators and crewmembers.



THE MICROGRAVITY ENVIRONMENT

If it were possible to build a tower reaching to the height of the Shuttle's orbit, the acceleration caused by gravity would be almost as strong at the top of the tower as it is on the ground. A person stepping off the top of this tower would drop to Earth. Why, then, do the Shuttle crewmembers float, and why does a microgravity environment exist for experiments?

Sir Isaac Newton hypothesized how an artificial satellite could be made to orbit Earth. He envisioned a very tall mountain extending above Earth's atmosphere so that friction with the air would not be a factor. He then imagined a cannon on the mountaintop firing cannonballs parallel to the ground. As each cannonball was fired, it was acted upon by two forces. One force, the explosion of the black powder, propelled the cannonball straight outward. If no other force were to act on the cannonball, the shot would travel in a straight line and at a constant velocity. Newton knew, however, that a second force would act on the cannonball: the presence of gravity would cause the path of the cannonball to bend into an arc, ending at Earth's surface.

Newton imagined other cannonballs traveling farther from the mountain as the cannon was loaded with more black powder each time it was fired. With each shot, the cannonball's path would lengthen, and soon it would disappear over the horizon. Eventually, if a cannonball were fired with enough energy, it would fall entirely around Earth and come back to its starting point. If gravity were the only force that could interfere with the cannonball's motion, it would continue circling Earth – in orbit.

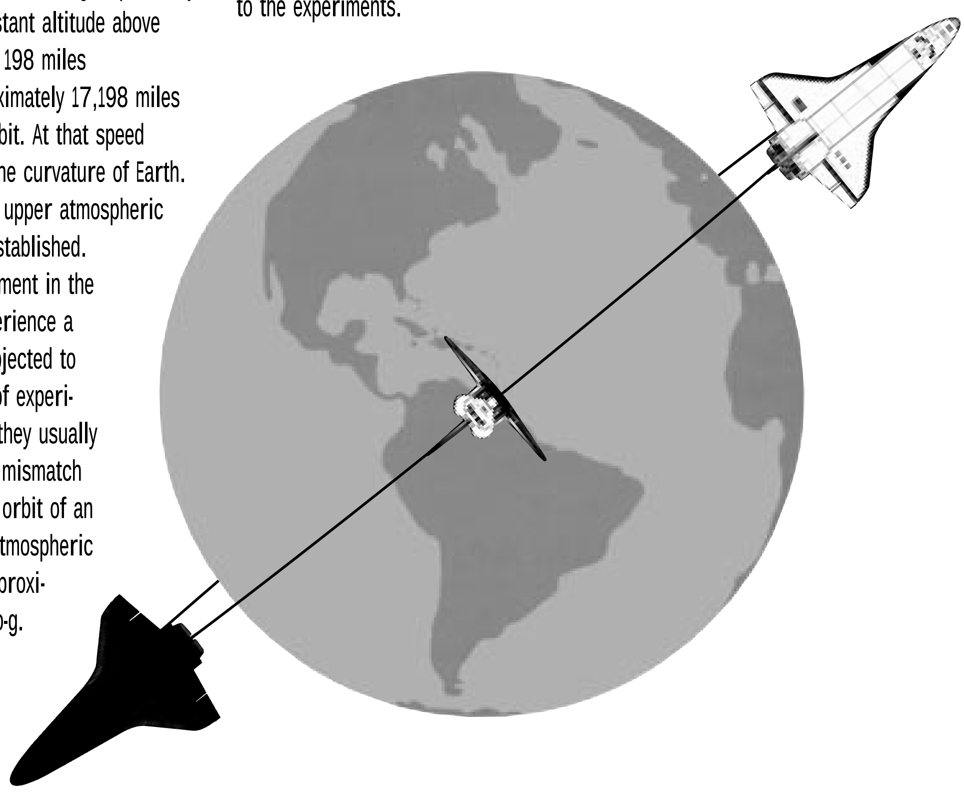
The Space Shuttle stays in orbit above Earth in a similar way. It is launched in a trajectory that arcs above Earth so that the orbiter is travelling at precisely the speed that will keep it falling while maintaining a constant altitude above the surface. For example, if the Shuttle climbs to an orbit 198 miles (320 kilometers) high, it must travel at a speed of approximately 17,198 miles (27,740 kilometers) per hour to achieve and maintain orbit. At that speed and altitude, the Shuttle's falling path will be parallel to the curvature of Earth. Because the Space Shuttle is freefalling around Earth and upper atmospheric friction is extremely low, a microgravity environment is established.

The term *microgravity* is used to describe the environment in the Shuttle and Spacelab because the experiments do not experience a perfect freefall state. As the Shuttle orbits Earth, it is subjected to small decelerations from atmospheric drag. The location of experiments inside Spacelab is another important factor. Since they usually are not located at the Shuttle's center of gravity, a slight mismatch is created between the path of the Shuttle's orbit and the orbit of an experiment inside. This combination of off-alignment and atmospheric drag alters the experiment's freefall by a force that is approximately one millionth the force of Earth's gravity – a micro-g.

COLUMBIA'S ATTITUDE AND ORBITAL INCLINATION

The attitude and orbital inclination of *Columbia* during the LMS mission have been determined by two factors: the need to maintain circadian rhythms for the crew and the necessity of reducing directional and vibrational forces for the microgravity science experiments. The 39° inclination will place the orbiter over Florida approximately the same time every morning, precluding the need for the crew to be awakened early for landing and allowing them to maintain the same sleep/wake rhythms they are accustomed to on Earth.

To maintain a tightly controlled path through space, the LMS attitude will keep the tail of the Shuttle pointed toward Earth, a position called the *gravity-gradient* attitude. In this position, the vehicle attitude is maintained primarily by natural forces, reducing the need to fire the orbiter's thrusters to maintain attitude control. Because thruster firings accelerate and vibrate the spacecraft slightly, they can be detrimental to sensitive experiment operations. The gravity-gradient attitude permits long-term vehicle stability and maintains the microgravity environment inside Spacelab with minimal disruption to the experiments.



STEPS TO MISSION SUCCESS

The mission management team coordinates the planning of all the activities necessary to accomplish a mission. These activities include coordinating flight operations with Johnson Space Center (JSC), ground-processing operations with Kennedy Space Center (KSC), and individual experiment operations with Principal Investigators (PIs). By launch day, everyone involved is working together as a team with one common goal: a successful mission with maximum scientific return for each investigation.

EXPERIMENT SELECTION

Proposals are received from the scientific community in response to NASA solicitations for research experiments. Proposed studies undergo a peer review process by a group of scientists who are leaders in their fields. Investigations are evaluated on the basis of intrinsic scientific merit and suitability for flight on the Shuttle. Foreign agencies have similar procedures. As experiments, objectives, and associated hardware are developed for flight, they are subjected to further reviews, with final approval for flight given by NASA Headquarters.

SCIENCE PLANNING

After experiments are selected, an Investigator Working Group (IWG) is convened to guide the scientific planning of the mission. The committee is chaired by the Mission Scientist and includes the Principal Investigator for each experiment chosen for flight. The IWG meets periodically before and during the mission to guide the incorporation of the various experiments into a single payload and to coordinate the requirements of the investigators.

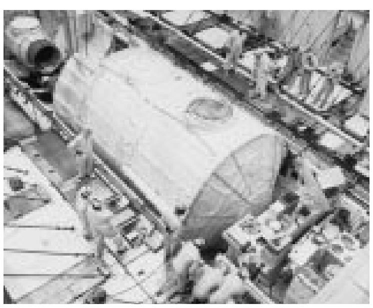
HARDWARE DEVELOPMENT

Experiment hardware is developed by NASA and other international space agencies in collaboration with investigators, universities, and private industry. The apparatus are designed both to fulfill research purposes and to fit with other experiments within the size, weight, and power supply constraints of the Space Shuttle and Spacelab. Several large instrument complements, called facilities, have been developed for repeated use by scientists on different missions. These are, in effect, mini-laboratories, each a self-contained unit for concentrated research in a particular discipline. A facility may occupy an entire experiment rack and may remain assembled between missions for reflight.

INSTRUMENT/PAYLOAD INTEGRATION

Payload integration occurs in several phases. Initially, the requirements of each experiment — volume, energy, power, data interfaces, and crew time — are evaluated, and a layout is designed to assure that all users can share the Spacelab accommodations compatibly. Later, instruments are shipped to the KSC launch site for assembly of the total payload and for installation into Spacelab according to the developed blueprint. Components are attached to experiment racks and the experiment support structure, and all circuits and connections are tested.

Approximately 7 weeks before launch, the Spacelab complement is placed inside the orbiter, and all connections are checked. Then the loaded orbiter is moved to the Vehicle Assembly Building to be attached to the external tank and solid rocket boosters. Finally, the fully assembled spacecraft is moved to the launch pad.



In the days preceding launch, animal and plant specimens are selected and samples are prepared. A few hours before the launch, technicians use the specially designed Module Vertical Access Kit to load the living and time-sensitive specimens into Spacelab. Similar items also are stored in the middeck at this time.

TRAINING

Although the crewmembers are professional astronauts or scientists, they must train for the mission to ensure the success of each investigation. The initial training may occur in the investigators' laboratories or at NASA centers, where the crew is instructed in the theory, hardware, and operation of the experiments. Training for integrated Spacelab experiment operations occurs at Marshall Space Flight Center, where in-flight operations involving the Spacelab computer system and integrated experiment facilities are simulated realistically in the Spacelab mockup in the Payload Crew Training Complex.

In addition to the crew, the Principal Investigators and the entire mission management team undergo training for their responsibilities. Everyone involved in the mission participates in simulations to practice planned operations, communication procedures, and problem-resolution techniques.

FLIGHT OPERATIONS

During a Spacelab mission, the mission management team monitors and manages payload operations from the Spacelab Mission Operations Control Center at MSFC. From there or from remote sites, Principal Investigators and their teams receive and analyze experiment data and interact with the crewmembers as necessary. The Mission Scientist and other key members of the mission management team, supported by a payload operations cadre, assess and respond to real-time information, replan as necessary, advise the crew of changes in the schedule, and work together to resolve problems and keep the mission flowing smoothly. A similar team at Johnson Space Center controls and monitors orbiter operations.

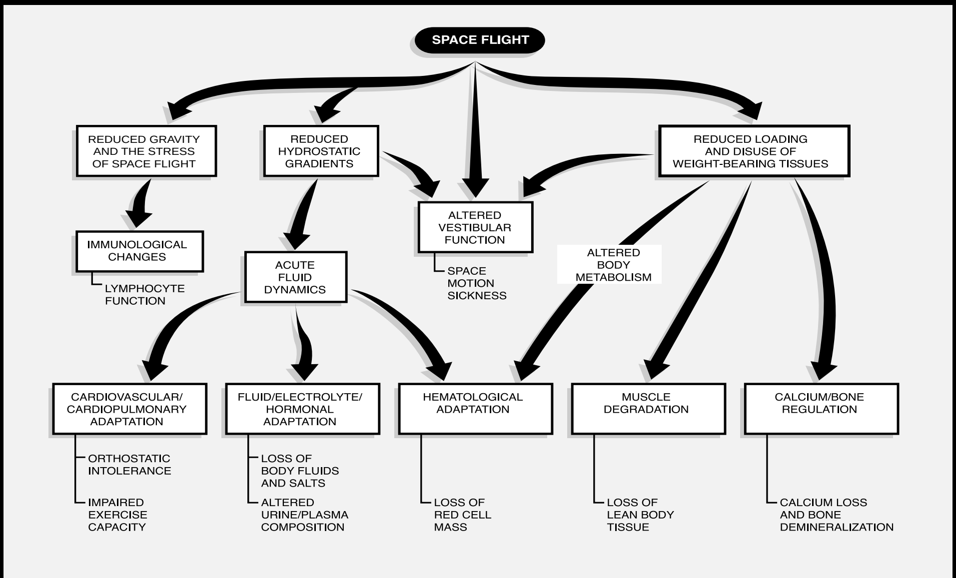
POSTMISSION ACTIVITIES

After landing, experiment samples are removed from the orbiter and returned to scientists for evaluation. Later, experiment hardware is returned to the space agency that developed it. Computer tapes, voice recordings, videotapes, and other data are organized and forwarded to investigators. Analysis of the data starts before the Shuttle touches down and may continue for several years. As results are analyzed, investigators prepare for publication, sharing the information with other members of the science community.

LIFE SCIENCES

Human Physiology

The reasons to study human physiology in microgravity range from the obvious — ensuring astronaut health — to the less obvious — improving health care on Earth. The human body is designed to operate in Earth's gravity field. Our skeletal structure, muscles, tendons, and ligaments support our weight against this constant pull. Other systems regulate the distribution of fluids, organize sensory input to provide balance and coordination, and provide a rhythm to the operations of the body. When the gravitational load is removed from the human body, as it is when a person travels in space, many complex — albeit natural — changes take place: bones and muscles become weaker, fluids shift toward the upper body, the daily rhythms of the body may be disrupted, and a person may suffer from motion sickness until the body adapts to the new environment.



Major physiological systems interact as the body adapts to weightlessness.

One of the goals of the LMS mission is to study the response of the human body to spaceflight. Experiments investigate acute changes that occur rapidly in the body during launch and ascent, as well as those that happen during the first few days of weightlessness and immediately after the Shuttle lands. Since it is scheduled for a 16-day flight, LMS provides an excellent opportunity to characterize adaptive changes that occur during longer stays in space.

Human physiology experiments selected for the Life and Microgravity Spacelab mission will allow scientists to study the effects of microgravity on the human body, specifically on musculoskeletal, metabolic, pulmonary, human behavior and performance, and neurological functions. Investigations are designed to eliminate redundant measurements on the test subjects and to maximize data that can be shared among investigators.

PRELAUNCH

For several months preceding the launch of *Columbia*, baseline data will be collected from LMS crewmembers for comparison with information gathered during and after the mission.

LAUNCH

When the astronauts strap themselves into the orbiter, their bodies immediately begin to change as fluids shift toward their heads while they sit with their backs toward the ground. Upon successful completion of the countdown, the thrust of the Shuttle pushes them

back in their seats, and they feel the pressure of liftoff as the Shuttle strains against Earth's gravitational pull. In less than 10 minutes, the crew is orbiting around Earth at more than 17,000 miles per hour. They feel a new sensation: near weightlessness, or microgravity.

ACUTE CHANGES

The astronauts' bodies respond quickly to the new environment. There is no gravitational load to pull blood and other body fluids toward the legs, and the fluids continue to shift toward the upper body or torso. Their faces become puffy, and their legs become thinner. The body's sensors in the heart and lungs may perceive that the body has too much fluid and may direct the kidneys and hormone-producing organs to get rid of part of it. Crewmembers also may feel less thirsty and drink less. After a few days, the body is operating with less fluid than it does on Earth. Blood volume is reduced, and the heart may not have to work as hard. Evidence indicates that all these changes are normal responses to weightlessness.

Preflight appearance

Inflight appearance

Changes in the neurosensory system (inner ears, eyes, and nervous system) complicate studies of the body's adaptation. When crewmembers are in weightlessness, they may be confused about body orientation. There is no perception of gravity to indicate up or down. Consequently, they may receive conflicting responses from their eyes and inner ears, which may result in symptoms similar to motion sickness. Scientists have been unable to develop effective countermeasures to prevent space motion sickness because they still do not understand it thoroughly.

LONG-TERM ADAPTATION

While the body adapts quickly, many physiological responses to spaceflight evolve over a longer period. For example, as the astronauts float through the Spacelab, their unused muscles may become deconditioned. Without gravitational loading on the skeletal system, the bones may lose calcium and strength. The musculoskeletal system needs careful study because the effects of weightlessness may take a greater toll on longer missions.

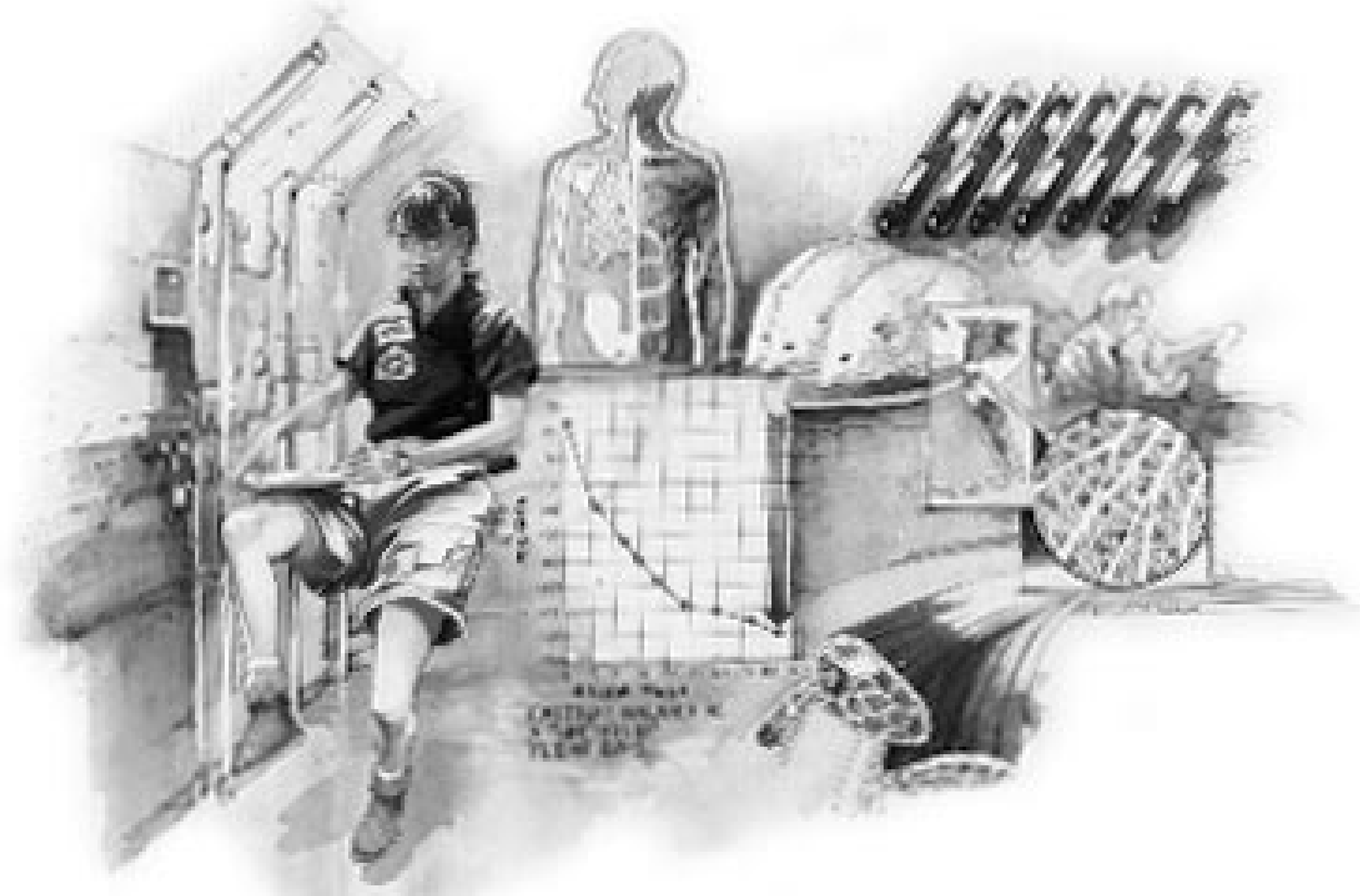
RE-ADAPTATION

Upon return to Earth, the astronauts' bodies again let them know that the gravitational loading has changed. Their hearts pump harder to circulate blood against the force of gravity. The decrease in fluid volumes that resulted from the early physiological response to microgravity can become a problem when gravity once again pulls fluids to the lower extremities, possibly causing crewmembers to feel weak or dizzy when they try to stand or even while sitting. Also, deconditioned cardiovascular systems and atrophied muscles may make it difficult for them to stand and exercise comfortably upon return to Earth. In space, the neurosensory system may have been ignoring some physiological cues that are needed on Earth to sense the position of the head and body. Upon return to Earth, the system is bombarded again with conflicting messages, and balance may be affected temporarily.

POSTFLIGHT

Studies after the mission are important to determine how and when the body returns to normal preflight conditions, how long it takes for this recovery, and what countermeasures can alleviate symptoms. Data gathered over the course of the mission may be shared among LMS investigators as well as with other researchers studying human physiological conditions and processes.

Human Physiology Discipline



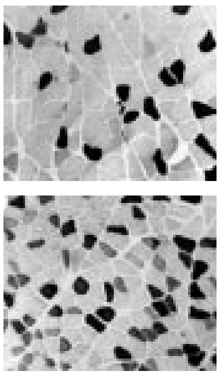
MUSCULOSKELETAL EXPERIMENTS

Bones and skeletal muscles provide humans with body structure and with the ability to move. The skeletal muscles, those that are attached to bones and make movement possible, are the focus of the LMS musculoskeletal investigations. These muscles consist of numerous elongated one-cell fibers that run for various lengths (often many centimeters) through the muscle. Some of these fibers, the slow-twitch muscle cells, generate force for prolonged, continuous activity; they are most active in resisting gravity and are important in maintaining posture. Other types of muscle cells, the fast-twitch fibers, produce force for rapid movement and exercise.

During spaceflight, the human body is no longer under gravity's influence, and the function of the musculoskeletal system changes in response to the altered demands imposed upon it. Because astronauts float within the orbiting spacecraft, their leg and back muscles are freed of the load-bearing stresses experienced on Earth as they support the weight of the body. Although the skeletal muscles continue to control and move the body, muscle fibers become smaller (atrophy) in the absence of gravity.

Since the early days of human spaceflight, the atrophy of skeletal muscles has been a recognized occurrence and the focus of scientific investigation. Studies on previous missions have documented a loss of muscle mass and a reduction in fiber size, as well as biochemical changes in muscles that oppose gravity. Significant atrophy of the skeletal muscles has been documented from NASA's Skylab program and Space Shuttle flights, as well as Russia's biosatellite Cosmos and Space Station Mir missions. From studies of rodents flown in space, researchers also have identified a fundamental shift in muscle energy sources (from fat to carbohydrates) in muscles that are composed predominantly of slow-twitch fibers. These muscles tend to atrophy more than those consisting primarily of fast-twitch fibers, and in some cases, the slow-twitch muscles even acquire the characteristics of fast-twitch muscles.

The adaptation of muscle and bone to weightlessness is an expected response to the microgravity environment, but the loss of muscle mass and changes in the ways muscles are used can become a disadvantage to astronauts upon return to Earth. Fortunately, these responses seem to be short-lived and reversible, but the effects of long-duration spaceflight on muscles and bones are not known. A comprehensive understanding of the changes in muscle structure and function in space and of the contributing physiological and cellular mechanisms is essential to the development of more effective countermeasures to these adaptations for both short- and long-duration missions. Also, this knowledge will contribute to our basic understanding of how muscles function on Earth.



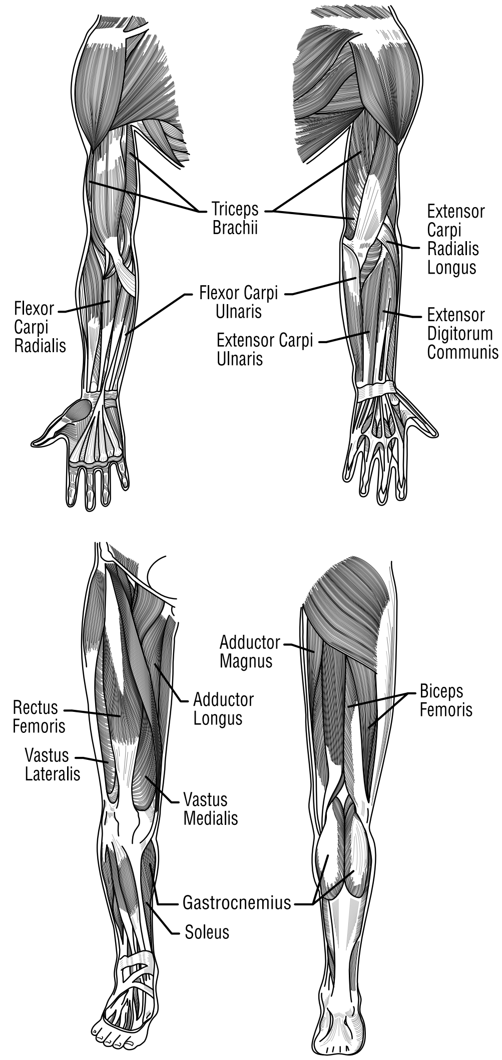
These light micrographs show the effect of microgravity on the size and type of muscle fibers in the leg muscles of rats. The larger cells (top) are from the muscle of a rat that remained on Earth and served as a control; the smaller cells (bottom) are from the identical muscle of a Spacelab-3 rodent, which was in Earth orbit for 8 days. The dark-stained fast-twitch muscle fibers are more numerous in the muscle of the flight animal.

Six LMS investigations (three sponsored by NASA and three by ESA) will continue the work of characterizing the effects of weightlessness on skeletal muscle function, performance, and biochemistry. Four of these studies have in-flight components, while two are conducted exclusively on the ground, before and after the mission. Each investigation concentrates on a different aspect of muscular adaptation; each also will generate information that enhances the findings of other experiments. For instance, some experiments test the right limbs; others, the left. Certain experiments investigate performance of the arms, while others study the legs. Investigations of the functional characteristics of whole muscles are complemented by those examining individual fibers from the same muscle, and the contractile properties of muscles are examined under different activation (voluntary or involuntary) regimens.

Of particular interest to LMS investigators are the muscles that move the ankle, knee, elbow, and wrist joints. Ankle extension is controlled primarily by two muscles in the lower leg, the soleus and the gastrocnemius, which form a muscle group commonly known as the calf. The soleus has a higher proportion of slow-twitch fibers than does the gastrocnemius, which has more fast-twitch muscle fibers. In the arm, the biceps flex and the triceps extend the elbow. These muscles, which are less critical in resisting gravity, usually consist of about equal percentages of slow- and fast-twitch fibers. Since the calf muscle group is an important anti-gravity muscle group, whereas the biceps of the arm are not, investigation of both allows comparison of the effects of weightlessness on weight- and non-weight-bearing muscle groups.

To investigate the specific questions of the LMS musculoskeletal scientists, the payload crewmembers will participate in comprehensive batteries of tests before, during, and after the mission to measure muscle performance, oxygen intake and utilization, muscle size and percentages of slow- and fast-twitch cells, and cellular characteristics. These results will be complemented by measures of the electrical responses of muscle tissue to controlled voluntary activation of muscles [electromyograms (EMGs)] and of electrical potentials produced by contractions of the heart [electrocardiograms (ECGs)]. The data gathered on LMS will provide a detailed picture of how and why the performance of the limb movements are affected by immediate and more prolonged exposure to microgravity.

In space, the human body naturally assumes a loosely tucked posture, and the antigravity muscles in the legs, back, and abdomen do not have to hold the body upright against the tug of gravity. Because these muscles are not required to work as hard in microgravity as they do on Earth, they tend to atrophy at a faster rate than the muscles that do not function primarily to resist gravity, such as the arm muscles.

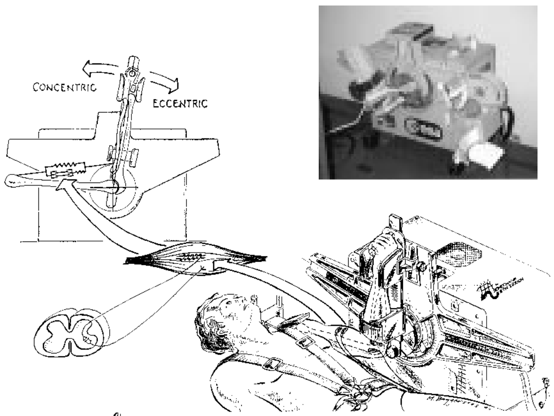


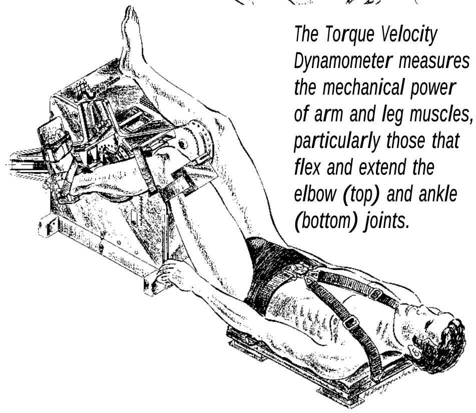
How skeletal muscle function and physiology change in microgravity is the focus of the six LMS musculoskeletal investigations. Of particular interest are muscles in the legs and arms.

TORQUE VELOCITY DYNAMOMETER

The complementary nature of the LMS musculoskeletal experiments has engendered the development of a multi-purpose workstation to support each of the investigations: the Torque Velocity Dynamometer, or TVD. Developed by the European Space Agency specifically in response to the science requirements of this mission, the TVD is the platform for many of the in-flight musculoskeletal activities, as well as for those that establish baseline measurements before the flight and provide follow-on data after the orbital segment of the mission.

The TVD measures torque – the turning effect produced when force is applied to a rotational axis. For TVD measurements, contracting muscles associated with elbow and ankle joints apply force against a lever arm attached to a shaft on the dynamometer's motor (the rotational element), and a sensor in the TVD measures the resulting torque. Because the muscles produce force both as they contract to move the arm or foot and also as they resist being moved by external influences, the TVD provides a measurement of torque under both conditions: as the subject voluntarily moves the elbow or ankle to rotate the dynamometer's motor and as the subject actively resists having the elbow or ankle moved by the lever arm as it is driven by the motor. In addition to torque measurements, the TVD gauges the rate at which an arm or foot moves through its range of motion (the angular velocity of the elbow or ankle). These types of mechanical measurements enable the science teams to calculate levels of muscle perfor mance and function, including strength, energy expenditure, and fatigue.





The Torque Velocity Dynamometer measures the mechanical power of arm and leg muscles, particularly those that flex and extend the elbow (top) and ankle (bottom) joints.

The main unit of the dynamometer sits on the floor of the Spacelab center aisle. Inside are the torque sensor, motor, gears, and electronics that drive the device. Special knee, foot, and arm restraints, called Human Interfaces (HIFs), mechanically connect the test subject to the TVD. A moveable plate attached to the outside of the main unit positions and fixes the HIFs to restrain any limb movement that would compromise the experiments. The leg HIFs have knee and shin restraints, while the arm HIFs prevent wrist rotation and upper forearm movement. Another restraint prevents the shoulder from reacting to the torque produced by a flexing elbow. The subject support plate, a cushioned platform outfitted with shoulder and waist belts to restrain the torso, can be positioned so that it allows the test subject to perform the experiments in comfort and without unnecessary movement.

The dynamometer can hold an arm or foot in a stationary position with the elbow or ankle at a fixed angle for isometric exercises (the subject contracts the muscles without moving the lever arm of the TVD). The TVD also can move the arm or leg to alter the angle of the elbow or ankle so that the attached muscles change length at a programmable, constant speed (isokinetic measurements). In addition, the TVD supports isotonic measurements while the muscles are either shortening (concentric movement) or lengthening (eccentric movement). In the isotonic experiments, the muscles either move against or are moved by a specific load or resistance applied by the TVD. During concentric movement, the TVD measures torque as the arm or leg muscles actively contract (shorten) against a known resistance, decreasing the joint angle; during eccentric movement, the device records the torque generated as the TVD causes the joint angle to increase while the test subject actively contracts the limb muscles, resisting the movement.

To perform the musculoskeletal experiments, the subject lies on the support plate, strapping on the torso restraint belts and securing the limb into the appropriate HIF. Following instructions displayed on the TVD control/display panel, the crewmember then performs a safety check of the dynamometer. After the safety test is completed, the crewmember uses either the TVD control/display panel or an external microcomputer to begin the experiment run. The microcomputer captures the resulting measurements and displays these to the subject.

Effects of Weightlessness on Human Single Muscle Fiber Function

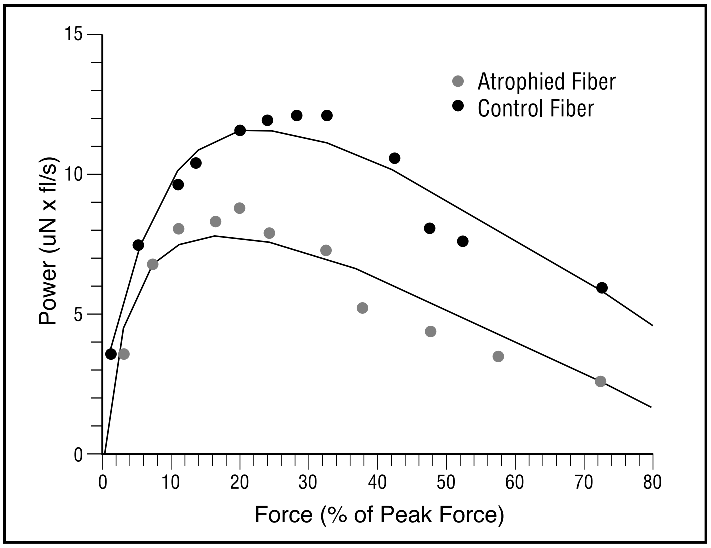
Principal Investigator: Dr. Robert H. Fitts, Marquette University, Milwaukee, Wisconsin

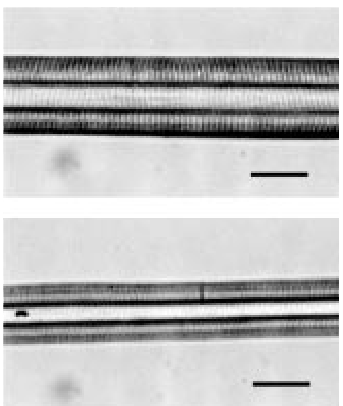
Co-Investigator: Dr. David L. Costill, Ball State University, Muncie, Indiana

This experiment investigates the cellular causes of muscular atrophy and weakness in space. Investigators will establish the extent to which changes in cell function affect skeletal muscle function and performance, as well as the time course for any such changes. The results of assessing the work capacity of individual muscle fibers as well as intact muscle groups will contribute to a better understanding of microgravity-induced muscle atrophy and will help refine existing countermeasures against the deleterious effects of weightlessness on human muscle performance. An increased understanding of the cellular processes involved in muscle wasting also may be relevant to scientists concerned with the processes of aging.

Specifically, the science team will study the relation of oxygen consumption (VO_2) to muscle function and performance. Oxygen uptake and energy expenditure are closely related. When slow-twitch muscles are exercised, they rely primarily on an aerobic process (one requiring oxygen) to extract the energy stored in carbohydrates, fats, and proteins. Fast-twitch fibers are more dependent on energy produced by the anaerobic breakdown of stores of glycogen. If a human's maximal oxygen uptake capacity declines in space, the slow-twitch muscles may not be as efficient because of their increased dependence on anaerobic energy sources.

The experiment has three components: cardiovascular exercise testing, leg muscle (right calf)

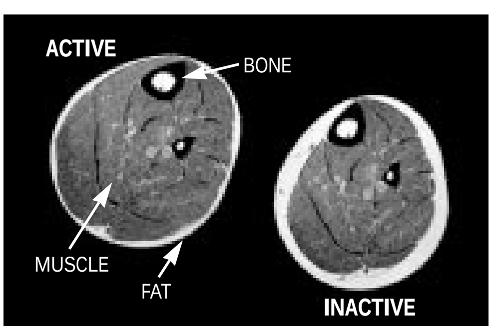




Photomicrograph (left) and power curves (above) of single skeletal muscle fibers from the soleus muscle show the normal (control) and atrophied (following 2 weeks of leg unloading) conditions. The fiber sizes are 71 and 52 microns, respectively, and the bar line represents 50 microns. The effect of leg unloading reduced the peak power from 12.2 to 8.8 μN x fl/s (where μN = micronewton; fl = fiber length, and s = seconds).

testing, and muscle biopsy. In the cardiovascular exercise element, investigators will compare preflight, in-flight, and postflight measurements of each payload crewmember's capacity to take oxygen into the body (the maximum oxygen consumption) to determine any changes in uptake capacity. Muscle testing will evaluate how well the right calf muscles contract and how long they can work before tiring. Finally, scientists will obtain biopsies of crewmembers' muscle tissue. Physiological and biochemical assays of single fibers isolated from the biopsies will disclose any changes that may have occurred at the cellular level.

Before the mission, each crewmember will exercise on the cycle ergometer, pedalling at various levels of resistance. The ergometer workloads, the revolutions per minute achieved, the amounts of carbon dioxide and oxygen in both inhaled and exhaled air during exercise, and the subject's heart rate will be used to calculate a preflight baseline maximum oxygen-uptake value. The baseline measurements of muscle performance (fatigability, comparison of muscle force to velocity, and maximal voluntary contractions) will be established with the Torque Velocity Dynamometer. Muscle fiber biopsies will be taken 45 days before launch and as soon as possible after landing.



The photo indicates the changes that occur in calf muscle size with inactivity.

During the flight and at selected times after the mission, each of the payload crewmembers will exercise on the ergometer at incremented workloads, exactly as was conducted preflight, until they reach maximal oxygen uptake. The in-flight test will be performed at the beginning, middle, and near the end of the mission. The results will provide the time course and extent of oxygen-uptake change resulting from adaptation to the microgravity environment. Using the Exercise Breathing Apparatus, each crewmember will breathe cabin air, while the expired air will be sampled and analyzed for oxygen and carbon dioxide in a gas analysis system. An electrocardiogram will record heart rate.

During the mission, each subject will test calf muscle performance using the Torque Velocity Dynamometer. With the ankle stabilized at a specific angle, the subject will perform three isometric contractions, the strongest of which will determine maximal voluntary contraction. To define muscle fatigability, the subject will execute repeated maximal contractions over a 45-second period. Muscle force compared to velocity will be characterized as the subject makes three isokinetic contractions at six distinct angular velocities. A comparison of the cellular studies with the whole muscle performance will allow the research team to determine the extent to which the microgravity-induced decline in performance can be attributed to specific changes within the muscles, as opposed to neural or cardiovascular factors.

Relationship of Long-Term Electromyographic Activity and Hormonal Function to Muscle Atrophy and Performance

Principal Investigator: Dr. V. Reggie Edgerton, University of California at Los Angeles, California

Co-Investigators: Dr. John Hodgson and Dr. Roland Roy, University of California at Los Angeles, California; Dr. Richard Grindeland and Dr. Malcolm Cohen, NASA/Ames Research Center, Moffett Field, California

Degradation in skeletal muscle function associated with spaceflight may be caused, at least partially, by altered motor function. This experiment tests the hypothesis that the inactivity of muscles in space modifies a person's ability to control movement. It also tests the body's ability to secrete chemicals that can protect against muscle atrophy and weakness.

The experiment has four segments: a 24-hour EMG test, a torque-velocity/motor-control task, a fatigue test, and an endocrine response to exercise activity. The 24-hour EMG test will identify the subject's muscle activity levels during routine activity, measuring electrical impulses through 12 electrodes placed on 5 muscles on the right leg and arm. Once during each of three 24-hour tests, each payload crewmember will perform movements of the right leg and arm, using the Torque Velocity Dynamometer to determine levels and patterns of EMG activity at maximum and submaximum levels of effort. Also, in this second segment of the experiment, subjects test their ability to apply pressure by compressing a hand-grip dynamometer, a device that measures grip strength. These tests will provide information on the strategies of the nervous system to regulate controlled muscular activity and on how the microgravity environment modifies these neural

HARDWARE SUPPORTING MUSCULOSKELETAL INVESTIGATIONS

The LMS musculoskeletal studies rely on a number of other investigative tools in addition to the Torque Velocity Dynamometer. One instrument, the Percutaneous Electrical Muscle Stimulation (PEMS) device, stimulates muscles electrically. The PEMS generates precise electrical stimuli to produce involuntary muscle contractions. When an electrical pulse of known form, length, intensity, and frequency is applied to a muscle, investigators can evaluate some key mechanical features, especially twitch characteristics: twitch force, time to peak tension, rate of rise of tension, half-relaxation time, and twitch duration. With the PEMS, investigators also can cause continuous contractions (a condition called tetanization) in selected muscle fibers by stimulating the muscle at a chosen frequency. In addition, the PEMS is a reliable tool for assessing maximal muscle contraction and enables a comparison of the various factors causing muscle fatigue, as well as a correlation of fatigability with a muscle's fiber-type composition.

The Ergometer III made its first flight on the historic STS-71 mission, which returned the Mir-18 crew – including American Astronaut Norman Thagard – to Earth after 4 months aboard the Russian space station. The ergometer was one of the instruments used to gather biological data on the returning Mir crew. Here, Cosmonaut Vladimir N. Dezhurov (with his back to the camera) exercises on the ergometer, while other crewmembers, including Thagard (lower right), conduct related life science experiments.

The musculoskeletal investigations also share a collection of equipment with the life sciences experiments that are gathering data on the body's maximal oxygen uptake (VO_2). The shared Maximal VO_2 Hardware includes a cycle ergometer; a breathing apparatus; a gas analysis device; a signal conditioner, which supports the gathering of electrocardiograms and electromyograms; a microcomputer; and an environmental monitoring system.

The Ergometer III is a next-generation cycle ergometer, first flown on the Spacelab-Mir mission, STS-71, in June 1995. On the LMS mission, it will provide investigators with qualitative measurements of the stress induced by exercise. Unlike its predecessors, which resembled the familiar vertical stationary bicycle exerciser, the Ergometer III is a horizontal cycle. Wearing a lap belt, the subject sits in a recumbent position, with legs pedalling roughly parallel to the floor. To create and maintain a constant workload, the ergometer has a large, weighted flywheel surrounded by a braking band to resist the subject's pedalling. An optical sensor translates the flywheel motion into revolutions per minute, so that the amount of work done by the leg muscles can be calculated from the speed of the flywheel and the amount of force being applied to the braking band. A control/display unit provides performance feedback to the crew and also to science teams on the ground. The ergometer will be mounted on the Spacelab center aisle.

The Exercise Breathing Apparatus lets the subject pedalling the ergometer breathe cabin air and exhale into a breathing bag, the Bag-in-Box. GASMAP, the Gas Analyzer System for Metabolic Analysis Physiology, will analyze the oxygen and carbon dioxide in the inhaled and exhaled air. A microcomputer and electronic control assembly will support data collection and data display, and the Temperature and Humidity Monitoring System will provide a record of Spacelab environmental conditions.

strategies. The results also may reveal the importance of muscle use in the learning and forgetting of motor skills and may shed light on whether unstressed muscles and their neural networks compensate appropriately so that they regain the ability to move precisely or to maintain the appropriate postures in both Earth's gravity and a microgravity environment.

The effects of spaceflight on the fatigability of the ankle extensors (calf muscles) will be tested by having crewmembers perform a series of repetitive submaximal and then maximal isometric contractions. Both the torque of the ankle (force output) and the electrical activity (EMG) of the ankle extensors will be measured throughout the fatigue tests. These data will provide an indication of the relative importance of neural fatigue, as compared to muscular fatigue, helping to explain changes in motor performance and how the gravitational environment affects these responses.

The final component of this investigation is designed to test hormonal response to the fatigue test. The hormone of primary interest for this test is growth hormone, which will be measured from venous blood samples taken from the arm. The tests will be performed early in the mission and toward its end.

On-orbit results will be compared with pre- and postflight data to determine the effects of microgravity on the level of muscle activity, ability to control muscles, and capacity to secrete growth hormone. These findings may influence the development of effective measures to reduce in-flight muscle atrophy. In addition, the results of this investigation have implications for individuals who have limited muscular activity on Earth because of illness, aging, or injury. An understanding of the importance of muscle activity in maintaining muscle size and normal function will provide a basis for prescribing effective exercise for people recovering from long periods of immobility and other conditions associated with muscle atrophy.

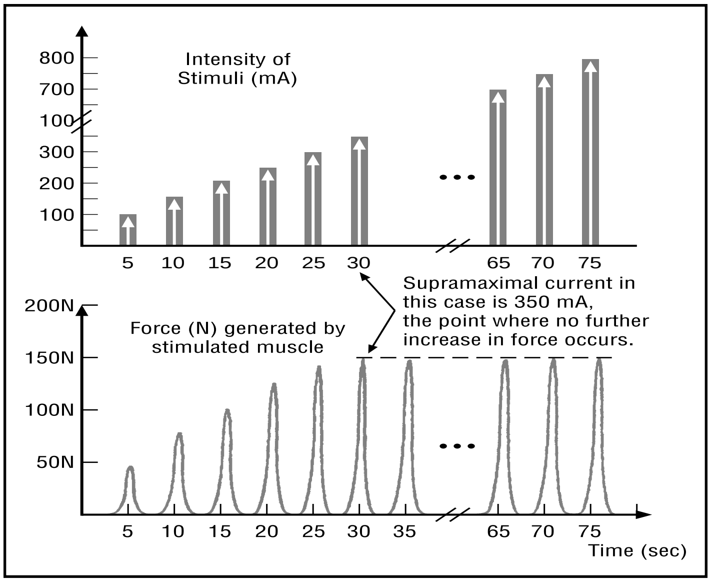
The Effects of Microgravity on Skeletal Muscle Contractile Properties

Principal Investigator: Prof. Dr. Paolo Cerretelli, Central Medical University, Geneva, Switzerland

Co-Investigators: Dr. Marco V. Narici, Institute of Advanced Biomedical Technologies - National Research Council, Milan, Italy; Dr. Bengt Kayser, Central Medical University, Geneva, Switzerland

Musculoskeletal results from previous missions indicate that microgravity conditions induce muscle atrophy. This experiment examines the contractile properties of the calf muscle group in the left leg to identify the effects of selective fiber atrophy on muscle function. The science team anticipates that atrophy will be greater in the soleus, because of its higher percentage of slow-twitch muscle fibers. Using the Percutaneous Electrical Muscle Stimulation (PEMS) device, an instrument that stimulates muscles electrically, the investigators can study muscle mechanics independently of voluntary control. In addition, the PEMS will apply electrical stimulation during maximum voluntary muscle contractions to determine the ability of the astronaut to activate the calf muscle at will. Torque (twitch) responses to the stimulations will be measured with the Torque Velocity Dynamometer. Magnetic Resonance Imaging (MRI) scans of the muscles before and after the mission will complement the PEMS and TVD data.

If the soleus muscle does exhibit greater atrophy than the gastrocnemius, the calf muscle group as a whole should need less time both to reach peak contraction levels and to relax fully. Investigators also expect that soleus atrophy will result in reduced maximum voluntary contraction and that the calf muscle group will tire faster as a result of atrophy of the fatigue-resistant slow-twitch fibers. Results of this experiment will be integrated with additional MRI, microscopic, hormonal, biochemical, and electromyogram data from the other musculoskeletal studies to develop a comprehensive description of the time course of early changes in muscle structure and function in space.



To determine a subject's Supramaximal Current Intensity, the plantar flexor calf muscle group is stimulated with electrical stimuli [100 milliamperes (mA)], increased in 50-mA steps every 5 seconds. When increases in stimulation produce no additional increase in torque (as measured by the TVD), the value of the Supramaximal Current Intensity under these experiment conditions is known. In this example, the subject's Supramaximal Current Intensity is 350 mA.

In preparation for the mission, each payload crewmember will undergo Magnetic Resonance Imaging to establish two preflight measurements of the calf muscle: cross-sectional area and volume. Ankle flexing activities will establish baseline measurements of torque, correlated to applied current. After the flight, the scans and performance protocols will be repeated.

During the mission, the PEMS will stimulate a crewmember's calf muscles to contract to determine a Supramaximal Current Intensity (SMCI), the intensity of stimulation at which there is no further increase in twitch torque. To assess the relationship between ankle angle and torquing force of muscles that extend the foot (plantar flexors), the ankle will be flexed at several different angles, a stimulus applied, and twitches measured. Muscle twitches also will be used to assess maximal voluntary contraction; while the crewmember contracts the calf muscles, two electrical stimuli at the SMCI level will be applied. If the voluntary contraction is below the maximum, the stimuli will excite those muscle fibers that are not activated voluntarily, producing an increase in force above that generated voluntarily. In another regimen, the force of the muscle will be measured while being stimulated at varying frequencies (the frequency-force relationship). Muscle atrophy is expected to produce a selective loss of force at specific frequencies. Finally, muscle fatigability will be evaluated with repeated stimulations. This protocol will show the consequences of selective slow-twitch muscle atrophy on the fatigue properties of the calf when it is made to contract beyond volitional control.

Effects of Microgravity on the Biomechanical and Bioenergetic Characteristics of Human Skeletal Muscle

Principal Investigator: Dr. Pietro E. di Prampero, University of Udine, Udine, Italy

Co-Investigators: Dr. Jachen Denoth and Dr. Edgar Stüssi, Swiss Federal Institute of Technology, Zurich, Switzerland; Dr. Carlo Capelli and Dr. Stefania Milesi, University of Udine, Italy; Dr. Jean-Françoise Marini, University of Aix-Marseille, France

A comprehensive understanding of skeletal muscle response to the space environment includes evaluation of the effects of microgravity on the relationships both between muscle length and the force it can generate and between force and muscle velocity during contraction. This experiment studies the maximal torque that subjects can exert voluntarily during either isometric or isokinetic contractions.

Studies on isolated muscles have shown that the maximal velocity with which a muscle can shorten is inversely related to the applied load. Investigators are interested in determining whether and to what extent this inverse relationship changes in microgravity. Also, since the force generated by the contractile component of the muscle is transmitted to the bone by elastic structures in series with the muscle, this experiment will analyze the relationship between muscle force and the length that the elastic structures stretch.

Using the TVD, each payload

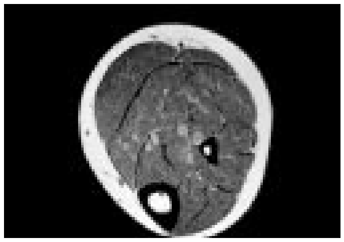
crewmember will exert a series of short maximal contractions with the flexors and extensors of the elbow and the plantar flexors of the ankle. These contractions will be performed at different joint angles and at various velocities of muscle eccentric and concentric contractions. To determine the role of neural input on the total force output of the muscles, electromyograms of contracting arm and calf muscles also will be collected. These activities will occur before, during, and after the mission, with the in-flight data being downlinked to the science team. Also, LMS findings will be complemented by the results of a bedrest study conducted at NASA/Ames Research Center before the mission.

Magnetic Resonance Imaging After Exposure to Microgravity

Principal Investigator: Dr. Adrian LeBlanc, The Methodist Hospital and Baylor College of Medicine, Houston, Texas

Co-Investigators: Dr. Linda Shackelford, NASA/Johnson Space Center, Houston, Texas; Dr. Harlan Evans, Baylor College of Medicine and Krug Life Sciences, Houston, Texas; Dr. Chen Lin, Baylor College of Medicine, Houston, Texas; Dr. Thomas Hedrick, The Methodist Hospital, Houston, Texas; Dr. M. Stewart West, Baylor College of Medicine, Houston, Texas

After the 8-day flight of Spacelab-J in September of 1992, the crew showed evidence of significant atrophy in their calf, thigh, and lower back muscles. This ground-based experiment is designed to document comparable changes in the muscles of the LMS crew during the planned 16-day mission. Using Magnetic Resonance Imaging scans, the science team will quantify changes in the volume of individual muscles (soleus, gastrocnemius, quadriceps, hamstrings, adductors, intrinsic low back, and

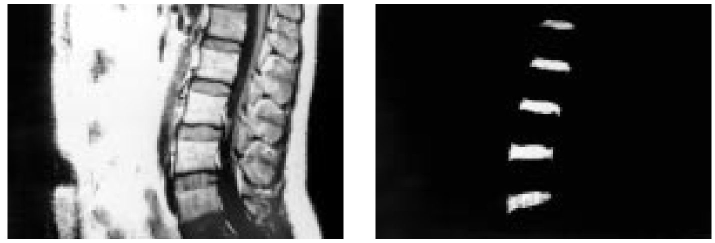


This cross-section of the calf muscle is one of 32 MRI slices used to determine individual muscle volumes.

psoas) and will determine the degree and rate of recovery to their preflight states. The MRI scans may demonstrate, for instance, whether the predominantly slow-twitch soleus atrophies faster than the predominantly fast-twitch gastrocnemius. Muscle volume will be compared to muscle performance measurements gathered on orbit during other experiments. Dual photon X-ray absorptiometry, or DEXA, will be used to obtain total body and regional fat and lean tissue mass, which will complement the MRI data. In addition, DEXA will be used to monitor fluid redistribution after flight.

Investigators also will study changes in the cross-sectional areas of intervertebral discs in the lower back; if significant expansion of the disc area is evident, researchers may improve their understanding of the causes of back pain reported by many astronauts. This experiment also will determine any differences in the ratio of fat and water in spinal bone marrow during 2 weeks in space. These findings may indicate alterations in the ability of the bone marrow to produce new red blood cells.

Muscle and total body scans of crewmembers will be performed 30 and 15 days before launch. The scans will be repeated within 24 hours of the Shuttle's landing and between 40 and 72 hours, at 2 weeks, and between 4 and 5 weeks after the mission.



Sagittal images through the spine, such as the one shown above (left), are used to obtain the cross-sectional area of intervertebral discs. Disc images (right) are extracted from the sagittal image, using a computer.

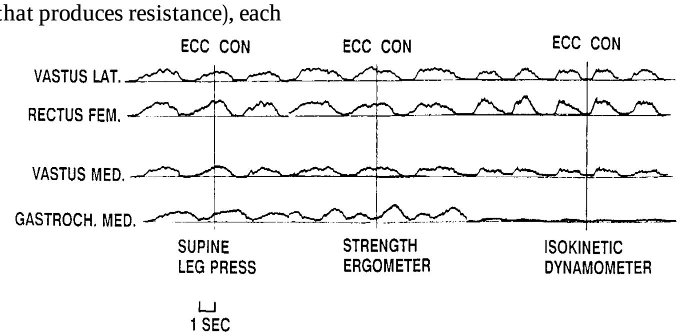
An Approach to Counteract Impairment of Musculo-Skeletal Function in Space

Principal Investigator: Dr. Per A. Tesch, Karolinska Institute, Stockholm, Sweden

Co-Investigator: Dr. Hans E. Berg, Karolinska Institute, Stockholm, Sweden

The study of changes in the performance of certain muscle groups is particularly beneficial to an understanding of the effects of orbital flight on muscles that usually bear weight and support the skeleton. This ground-based experiment identifies strength, power, and size changes in calf and thigh muscles occurring after extended exposure to weightlessness.

Before the mission, Magnetic Resonance Imaging scans of each crewmember's calf and thigh muscles will measure the cross-sectional areas. Using an inertia ergometer (one with a flywheel that produces resistance), each subject will establish individual values of force-velocity, joint angles, and joint angular velocity. Voluntary leg press exercises will define maximal force and power output for each subject. Electromyograms will determine the magnitude of neural drive to the muscles being exercised. These same procedures will be performed after the mission. By comparing the pre- and postflight data, investigators will help characterize changes in muscle performance in response to spaceflight. Specifically, the science team will study the force-velocity relationship of the knee extensor muscle group during concentric and eccentric actions. Also, they will seek to identify the mechanisms (e.g., muscle atrophy, decreased voluntary drive) responsible for impaired musculoskeletal function in response to orbital flight.

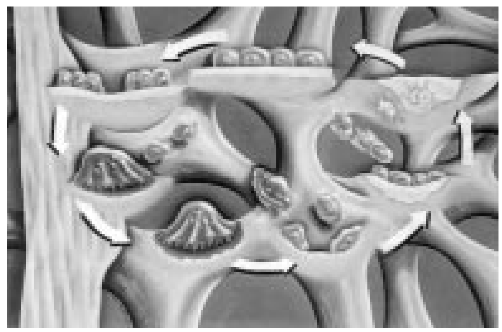


When the quadriceps muscles (vastus lateralis, rectus femoris, and vastus medialis) and the calf muscle (gastrocnemius) are exercised on different machines on Earth, the EMG recordings of these two muscle groups differ. The readings from the flywheel (strength) ergometer indicate that this machine exercises both muscle groups more uniformly than either a supine leg press machine or an isokinetic dynamometer. For this reason, the inertia ergometer was chosen as the platform for ground-based tests of the performance of these muscle groups before and after spaceflight. [The vertical lines in the chart above indicate the change from eccentric (ECC) to concentric (CON) activity.]

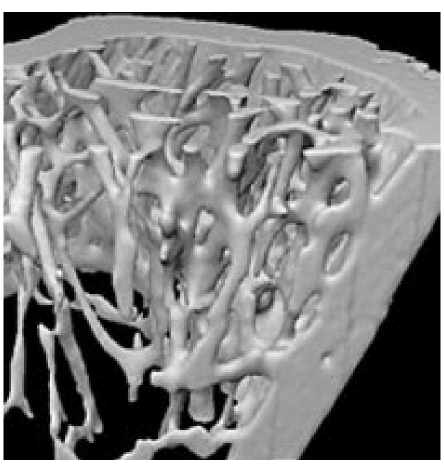
METABOLIC EXPERIMENTS

Spaceflight and adaptation to microgravity place a variety of stresses on the human body and result in changes to normal body biochemistry. For example, while the human skeleton is a dynamic system that is producing and removing bone continually from the body, investigations have shown that extra calcium leaves the bones of astronauts and enters the bloodstream almost immediately as they attain orbit. Preliminary studies indicate that the calcium balance is altered in microgravity by an increase in the rate of bone resorption (removal of calcium from bone into the bloodstream). The calcium is excreted in urine and through solid body wastes (feces). The urine calcium content appears to level off after approximately 30 days in space, but the fecal calcium increases continuously throughout a mission. When the astronauts return to Earth, excess calcium in the urine decreases during the second week and in the fecal matter in approximately 3 weeks.

This loss of calcium from the bones is a major concern to mission planners considering long-duration stays in space. Investigators want to know what triggers the response, whether the process is cumulative and/or reversible after extended space travel, and whether recovery upon return to Earth is complete. In addition, since the aberration is similar to osteoporosis, an illness that affects older people (especially women) on Earth, physiologists hope the information obtained from the space studies will provide valuable clues to the cause and treatment for this debilitating disease.



Starting from the extreme right and moving counterclockwise, this illustration shows the remodeling of trabecular bone. First, bone is destroyed (resorbed) by the large curtain-draped cells (osteoclasts), and then the resorbed bone is replaced with new bone by the rounded cells (osteoblasts).



Bone resorption during spaceflight may increase dramatically, even to the point of eating through individual trabeculae (the framework of the bone). If this occurs, loss of these structural supports will weaken the bone and can lead to its fracture, even under normal loads. Each individual's initial bone structure and calcium metabolic response to spaceflight will affect this outcome. Countermeasures to prevent the increased bone resorption, however, may be only partially effective if normal bone formation also is suppressed in space, as was seen in experiments with rodents on previous missions.

Other biochemical processes that may be altered in microgravity include protein metabolism and energy balance. Metabolism is the complex process by which the body utilizes nutrients, and the basal metabolic rate is the amount of energy the body releases in a given time by the breakdown of nutrients. On Earth, the body maintains a state of energy balance when the amount of energy available from ingested foods equals the amount of energy expended through daily activities. If people expend more energy than is in the foods they ingest, they are in a negative energy balance, and loss of body mass is the result. The effect of gravity on energy metabolism and energy expenditure is not known. Data from astronauts on Skylab indicate that energy expenditure may be increased during flight, but measurements on chaired monkeys flown on the Soviet satellite series Cosmos suggest the opposite.

To quantify and understand these biochemical changes better, LMS investigators will perform two experiments related to the physiological equilibrium of the human body and the adaptations experienced as a result of microgravity.

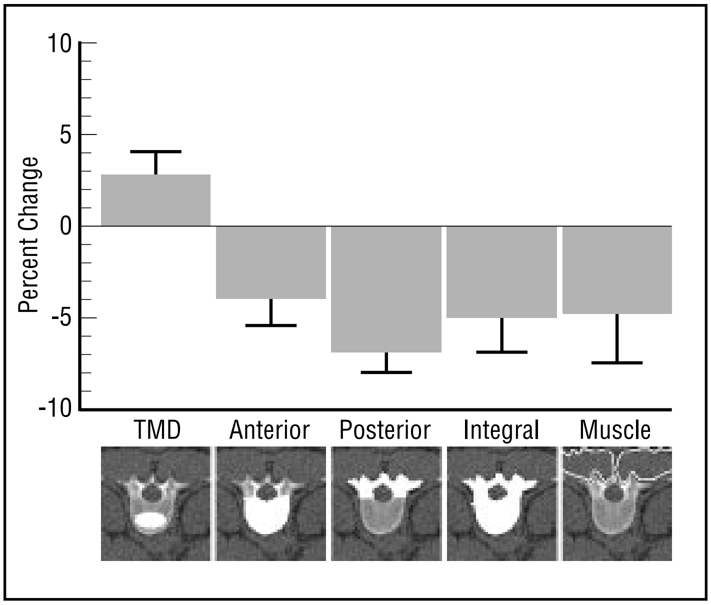
Direct Measurement of the Initial Bone Response to Spaceflight

Principal Investigator:
Dr. Christopher E. Cann, University of California at San Francisco, California

Co-Investigator: Dr. Claude D. Arnaud, University of California at San Francisco, California

The skeleton constantly is being broken down and rebuilt, with the processes normally occurring at equal rates. Spaceflight upsets this equilibrium, and the resulting imbalance between breakdown and reformation could cause lasting changes, even during a short-duration mission. The net cumulative effect of multiple short-term flights may be similar to that of extended exposure, creating concern for the health of astronauts who currently fly multiple short missions or who will be involved in the assembly phase of the international space station. This experiment is designed to interpret long-term effects of microgravity, based on each astronaut's individual in-flight response to the short-term exposure to space.

Scientists believe that reduced mechanical loads on the body in space induce the skeleton to discard bone it no longer needs and that the process of bone loss (resorption) begins almost immediately upon reaching microgravity. The purposes of this investigation are to test this hypothesis; to define the initial response to microgravity of the human calcium/bone homeostatic systems, which maintain the chemical equilibrium; and to gather data that will allow prediction of long-term consequences of short-duration spaceflights. Such



This illustration indicates regional changes in spinal bone density and muscle volume after long-term spaceflight. Computed tomography (CT) scans of cosmonauts after flights of up to 8 months show that most bone loss occurs in the posterior spine, where the postural muscles attach, while the lack of change in the density of the bone structure within the center of the vertebral body may be caused by the mechanical loading forces of in-flight exercise regimens, such as running on a treadmill. There are probably systemic factors causing overall bone loss, but exercise regimens may be able to overcome this loss, at least in those bones subjected to appropriate loading.

predictions may have clinical applications on Earth if a simple set of measurements can be found that is applicable to bone loss resulting from disuse or from postmenopausal osteoporosis, a disorder that is a serious concern for health officials, specifically for those involved in women's health issues.

Blood will be collected from crewmembers periodically. A rack-mounted centrifuge will separate the blood samples before they are frozen for postflight analysis.

Experiments during the First and Second Spacelab Life Sciences [SLS-1 (June 1991) and SLS-2 (August 1993)] missions verified that the human calcium regulatory hormone system functions normally in space, adapting to the high blood-calcium levels from increased bone breakdown by excreting more calcium in the urine and by decreasing calcium absorption in the intestine. These normal physiological adaptations are counterproductive to skeletal health, however, because they serve only to exaggerate the loss of bone. The 30- to 40-percent decreases in calcium absorption could cause significant problems if they persist in long-term spaceflights. In addition, increased calcium intake, which is a common therapy to combat osteoporosis on Earth, is expected to cause further urinary calcium excretion in space, increasing the risk for kidney stones.

During each SLS mission, both male and female crewmembers had similar metabolic responses to spaceflight, but the male response was more closely related to traditional theories of hormonal regulation of blood calcium, while the female response appeared to be more complex and may be related to reproductive hormones as well. This gender difference was unexpected but may provide clues to the basis of the predominantly female problem of osteoporosis on Earth. With this knowledge obtained from the SLS missions, the LMS investigators are targeting the mechanisms that initiate the process of bone loss within the first few hours on orbit to form a rational basis for the development of countermeasures to the bone loss of spaceflight.

At each meal from 10 days before the mission to 7 days after, crewmembers will ingest an oral tracer, a nonradioactive (stable) isotope of calcium, to distinguish calcium coming from the diet from that being resorbed from bone. Measuring the isotope ratios of calcium in blood, urine, and fecal samples taken before, during, and after the mission will allow investigators to determine directly the change induced by spaceflight in the calcium coming from bone. They also will be able to determine how each individual adapts to this in-flight change in bone resorption. All food, drink, and drug intake will be logged, and body mass will be measured by the Space Linear Acceleration Mass Measurement Device. This experiment will be the first to study metabolic balance in space since the Skylab studies of 1973-74.

Measurement of Energy Expenditure During Spaceflight with the Doubly Labeled Water (DLW) Method

Principal Investigator: Dr. Peter Stein, University of Medicine and Dentistry of New Jersey, Stratford, New Jersey

Co-Investigators: Dr. Reed W. Hoyt, Altitude Research Division/US Army Research Institute for Environmental Medicine, Natick, Massachusetts; Dr. Helen Lane and Dr. Randall W. Gretebeck, Biomedical Operations Laboratory, NASA/Johnson Space Center, Houston, Texas

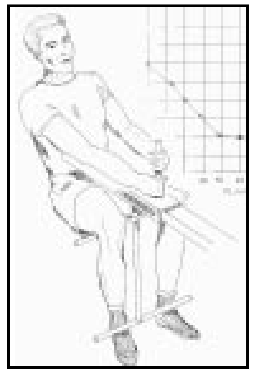
This experiment is the first attempt to measure the relationship between energy needs and dietary intake during spaceflight. The determination of human energy requirements in the microgravity environment is crucial to the design of life support systems and the accurate assessment of a person's ability to live and work productively in weightlessness. Available evidence is conflicting: some studies suggest an increase in energy output during spaceflight, while others indicate a decrease. Two consequences of a negative energy balance on Earth are the wasting of body protein (especially skeletal muscle) and the depletion of stored body fat. The protein loss may result in impaired performance, increased susceptibility to disease, and delayed healing of wounds. Such a loss during spaceflight may affect in-flight performance and impair the ability of the individual to function adequately during the critical phases of reentry and landing.

The doubly labeled water method is a highly accurate means of measuring energy output in a safe, time-efficient manner using only urine or saliva specimens for analysis. Water labeled with the nonradioactive isotopes deuterium (^2H) and oxygen (^{18}O) is ingested by the payload crew. The two isotopes leave the body at different rates. Deuterium leaves primarily in urine, while ^{18}O leaves in both water and exhaled carbon dioxide (CO_2). The difference in loss rates is equal to the rate of CO_2 production, which is directly related to the rate of energy expenditure. Crewmembers will provide samples of urine and saliva and will collect galley water to correct for any background changes in the drinking water. Also, they will monitor their dietary and drug intakes, keep daily activity logs, and measure body mass with the Space Linear Acceleration Mass Measuring Device. These measurements will be taken during 2 consecutive 6-day blocks of time before, during, and after the mission, a total of 36 days. Energy balance will be determined from the difference in energy intake as measured by the dietary log and actual energy expenditure as measured by the DLW method. Comparison of the in-flight data against the combination of the preflight and matched bedrest data will indicate whether the energy requirements of living and working in space are greater or less than those on Earth for comparable activity.

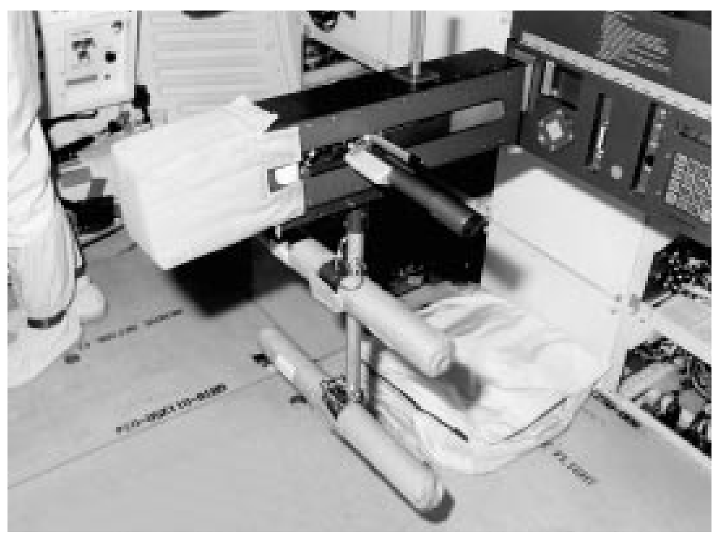
A better understanding of the relationship between dietary intake and energy expenditure is critical for assessing the long-term health and performance of the crew when planning for prolonged missions for the space station or for planetary exploration. The DLW method is particularly suitable for a Shuttle experiment because the experiment is non-invasive, crew time and equipment requirements are minimal, and the isotopes ^2H and ^{18}O are stable, naturally occurring tracers that are safe for human use.

SPACE LINEAR ACCELERATION MASS MEASUREMENT DEVICE (SLAMMD)

Weight is a function of gravitational force on mass. In the absence of gravity, however, mass can be measured using instruments such as the Space Linear Acceleration Mass Measurement Device.



The SLAMMD measures body mass by analyzing acceleration response to a spring pulling force. This pulling force is generated by a spring/cam/lanyard wheel assembly inside an enclosure in Spacelab Rack 12 and is transmitted to a handle attached to the front panel of the enclosure. After setting up the SLAMMD and handle, a crewmember will place his or her torso against the handle and secure that position by wrapping legs and feet around support bars. By pushing the handle, the subject sets the spring mechanism and locks the SLAMMD into alignment. The subject then releases the lock, and in approximately 4 seconds, the lock retracts, pulling the astronaut toward the rack with a 5-pound force. A microcomputer calculates the body mass, and the data appear on a liquid crystal display. A foam pad over the handle and a belly pad protect the astronaut during the measurement.



PULMONARY EXPERIMENT

The human lung is very sensitive to gravity; consequently, on Earth there are large differences in gas flow, blood flow, and gas exchange between the top and bottom areas of the lung. For example, pulmonary blood flow (perfusion) is greater near the bottom of the lung and is relatively smaller toward the top. Gas flow (ventilation) is similarly distributed, although there are still large differences in the matching of ventilation and perfusion between the top and bottom of the lung. Scientists once believed that these differences were primarily the result of the pull of Earth's gravity. Comprehensive studies of pulmonary function performed on the Spacelab Life Sciences-1 and -2 missions and the German D-2 Spacelab mission indicated, however, that much of the imbalance in the lungs between blood and gases was maintained in the microgravity environment. These results show that, while gravity plays a dominant role in the unevenness of lung function in humans, there are significant non-gravitational effects as well.

During the SLS-2 mission, studies of gas mixing in the small gas exchange regions of the lung (the acini) revealed that in microgravity these regions experienced a conformational change, which was unexpected and unexplained. Gas mixing in the acini is critical for gas exchange and often becomes compromised in people with pulmonary disease. Investigators have modified the tests performed on SLS-2 to obtain further information on this fundamental process, which is essential for life.

Pulmonary Function in Weightlessness

Principal Investigator: Dr. John B. West, University of California/San Diego, La Jolla, California

Co-Investigators: Dr. Ann R. Elliott and Dr. G.K. Prisk, University of California/San Diego, La Jolla, California; Dr. Manuel Paiva, Institut de Recherche Interdisciplinaire (Free University of Brussels), Brussels, Belgium

This investigation extends the studies of the human lung in four major areas. Investigators will study lung function after the stress imposed by heavy exercise in the microgravity environment; they will monitor the motion in the rib cage and abdomen to study the effects of microgravity on the musculoskeletal aspects of breathing during rest, during heavy exercise, and during deep breathing; they will make the first measurements in microgravity of the body's response to inhaled carbon dioxide, a response that may be altered by spaceflight; and they will continue to build on previous studies of how gas is distributed within the lung.

Dr. Millie Hughes-Fulford, Payload Specialist on SLS-1, performs the Astronaut Lung Function Experiment, following prompts on a display while breathing through a mouthpiece attached to the experiment. The breathing path is controlled by rotary valves under each hand.

Data will be collected before and during the flight, as well as several times in the 2 weeks following the mission to provide a comparison with lung function on Earth.

A sequence of breathing tests will measure the concentrations and volumes of inhaled and exhaled gases before and after exercise several times throughout the LMS mission. The data will be stored on board and downlinked simultaneously to the ground, allowing for interaction between the crew and the investigators. The Astronaut Lung Function Experiment (ALFE) hardware developed for SLS-1 and -2 has been modified and will be used with the addition of the Gas Analysis System for Metabolic Analysis Physiology mass spectrometer and microcomputer. Each crewmember will have an individual ALFE personal stowage kit, which consists of a mouthpiece and nose clip. The crewmember inhales either the ambient air of the Spacelab cabin or one of the test gases, depending on the activity being performed and the measurement being sought. Expired gases are monitored continuously while being directed either into the cabin, into the rebreathing bag, or into an exhaust bag. The Belgian-built Respitrace suit, a vest-like garment equipped with electronics connected to respiratory transducers located at the chest level and at the abdomen, will be used for the rib cage/chest motion studies.

A better understanding of the effects of gravity on the human pulmonary system ultimately may benefit clinical medicine on Earth. Also, a comprehension of pulmonary function in microgravity is important for long-term spaceflight.

HUMAN BEHAVIOR AND PERFORMANCE EXPERIMENTS

The ability of the human body to respond quickly to changes in the external environment as well as to physiological challenges is crucial for life on Earth and in space. This capability requires a highly organized communication system, which not only is receptive to various stimuli (light, sound, chemicals, or pressure) but also possesses an effective means of relaying this information to centers of recognition. On Earth, such mental acuity is affected by a number of factors, including fatigue, sickness, sleep, and changes in work/rest cycles and social conditions. In space, however, the effects of these catalysts may be magnified or inhibited, confounding normal physiological processes and diminishing effective behaviors.

Most organisms have behavior patterns that correspond to 24-hour cycles. These circadian rhythms are generated by internal biological clocks, which are regulated by external influences such as day/night cycles, seasonal changes, gravity, and Earth's rotation. For people orbiting Earth, there are 16 sunrises and sunsets in a 24-hour period, Earth's rotation and seasonal effects are eliminated, and there is virtually no gravity. In this environment, scientists can examine circadian rhythms in the absence of ordinary external cues. LMS investigations are designed to determine whether human behavior and performance are degraded by stress encountered during spaceflight and whether changes in social and work conditions negatively affect normal sleep cycles and waking performance.

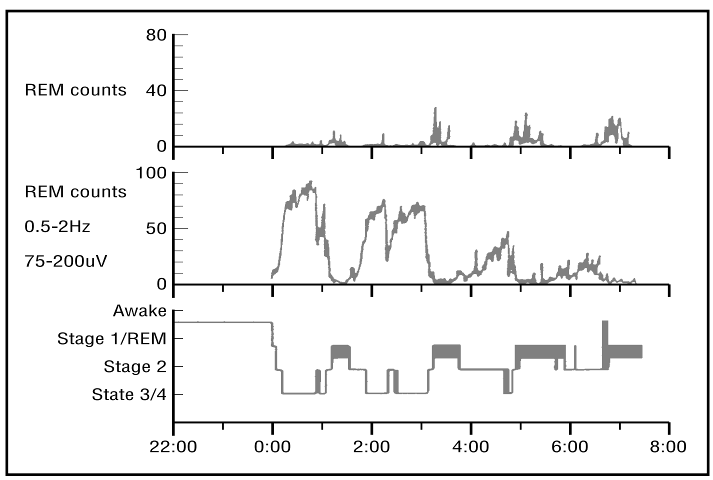
Human Sleep, Circadian Rhythms, and Performance in Space (SACS)

Principal Investigator: Dr. Timothy H. Monk, University of Pittsburgh, Pennsylvania

Co-Investigators: Dr. Daniel J. Buysse, University of Pittsburgh, Pennsylvania; Dr. Claude C. Gharib and Dr. Guillemette Gauquelin, Université Claude Bernard, Lyon, France

This is the first simultaneous study of sleep, circadian rhythms, and task performance in response to a microgravity environment. The experiment will evaluate effects caused by microgravity and by the absence of terrestrial time cues (zeitgebers) and normal social contacts. Scientists hypothesize that the severe weakening of social and physical zeitgebers during the mission and/or unusual conditions within the environment (microgravity, cramped conditions, and stress) will disturb circadian rhythms, which, in turn, will lead to poorer sleep and degraded task performance. Results may help explain challenges to the biological clock that occur on Earth as a result of shiftwork and jetlag.

For two 72-hour periods, each of the payload crewmembers will wear a special beltpack connected to a sleep cap with 10 electrodes attached to the head. The system will provide data about brain waves [electroencephalography (EEG)], eye movements (electro-oculography), and muscle tone (electromyography) while the crewmember is sleeping. These data allow scientists to categorize each minute of sleep by various types and depths. During the 72 hours, another beltpack recorder receives a signal from a temperature sensor indicating the crewmember's core body temperature every 6 minutes. Circadian rhythms also will be evaluated by measuring urine electrolyte and hormone concentrations at each voiding, by mood and activation testing every 2 hours during the wake cycle, and by performance testing before each meal. Crewmembers will keep a diary to record sleep quality and alertness on awakening and will answer end-of-shift questionnaires to evaluate workload, perceived effort, and fatigue. Except for the urine sampling, sleep data (polysomnography), and core body temperature sampling procedures, all aspects of the protocol will use the Payload General Support Computer. Data will be compared with pre- and postflight tests on Earth. Also, an identical ground study will be performed after the mission under the direction of Dr. Alexander Gundel of the Institute of Aerospace Medicine in Cologne, Germany.



The graph indicates a typical pattern of sleep stages from a young adult man, sleeping in a laboratory between 11:57 p.m. and 07:27 a.m. Periodically through the night, there are episodes of Rapid Eye Motion (REM) sleep, a sleep stage most associated with dreaming. There are four stages of non-REM sleep with 1 the lightest and 4 the deepest. Notice that the deepest sleep becomes less pronounced and REM sleep more pronounced as the night progresses (bottom panel). The other panels show the results of computer analyses for counts of actual eye movements during REM sleep (top panel) and counts of slow EEG waves during non-REM sleep (middle panel). When the biological clock (circadian system) is not functioning properly, this pattern of sleep stages is disrupted.

Microgravity Effects on Standardized Cognitive Performance Measures (PAWS)

Principal Investigator: Dr. Samuel Schiflett, USAF Armstrong Laboratory, Brooks Air Force Base, Texas

Co-Investigators: Dr. Douglas Eddy, NTI, Inc., Dayton, Ohio; Dr. Robert Schlegel, Oklahoma University, Norman, Oklahoma; Dr. Jon French, USAF Armstrong Laboratory, Brooks Air Force Base, Texas

Present-day astronauts are subject to a variety of stresses during spaceflight. These include microgravity, physical isolation, confinement, lack of privacy, fatigue, and changing work/rest cycles. On Earth, both fatigue and changing work/rest cycles degrade cognitive productivity. The purpose of this experiment is to determine the effects of microgravity upon thinking skills critical to the success of operational tasks in space. The principal objective is to distinguish between the effects of microgravity on specific information-processing skills affecting performance and those of fatigue caused by long work periods.

To measure these skills, the investigators use a set of computerized performance tests called the Performance Assessment Workstation (PAWS), which is based on current theoretical models of human performance. The tests were selected by analyzing tasks related to space missions and their hypothesized sensitivity to microgravity. Multiple subjective measures of cumulative fatigue and changing mood states also are included for interpreting performance data.

The performance tests will be presented to the astronauts on a laptop computer. The computer records the speed and accuracy of the astronaut's responses to rotated images, letter sequences, math calculations, spatial patterns, and recollection of numbers. It also records the individual's ability to track an unstable object on the computer screen with a precision trackball. Perhaps the most challenging test for the astronaut will be to do two things at one time, rapidly switching attention between the two tasks.

The astronauts will perform the test battery several times before the mission to establish reliable performance baselines and will perform the tests every other day while in orbit. After return to Earth, data will be collected from each of the astronauts to determine the rate of recovery from any detrimental effects of microgravity on information processing. By comparing in-flight and ground performance, the investigators will quantify the effects of spaceflight on each of the cognitive skills measured.

The PAWS results will help planners schedule work in space under a variety of cognitively degraded conditions, maximizing productivity and job satisfaction in astronauts who will live in space for extended periods of time.

Astronaut Carl Walz uses a laptop computer during the Second International Microgravity Laboratory mission (July 1994) to record responses to PAWS rotated images, spatial patterns, and questions regarding number and letter sequences and mathematical calculations. These and other tests are used to determine cognitive functioning during spaceflight.

LMS INTEGRATED BEDREST PROJECT

LMS is the first Spacelab mission involving human research experiments to perform a ground-based integrated science study before the flight. The study was performed in NASA's Human Research Facility at Ames Research Center, Moffett Field, California, in the summer of 1995 to provide a simulation of the human life sciences experiments. Non-astronaut volunteers participated in the bedrest studies, which mimic the effects of microgravity on Shuttle/Spacelab crews.

The volunteers lay on inclined beds with their feet elevated 6° above their heads, a position that causes changes to many organ systems similar to the physiologic changes experienced by astronauts during spaceflight. For example, bedrest participants may experience fluid shifts and loss of muscle and bone. The volunteers provided pre-bedrest baseline data in a normal upright mode for 2 weeks to allow for a control period. Following the timeline of the mission, they then had 17 days of bedrest (the anticipated length of the LMS mission), followed by an ambulatory 2-week recovery period.

During the time subjects were restricted to bed, special or modified equipment was needed: equipment apparatus and controls were lowered to bed height, and subjects exercised on an ergometer that could be pedaled from a horizontal position. LMS investigator teams and medical personnel were present throughout each phase of the study, and members of the LMS crew visited the subjects to learn more about what could be expected during the space mission.

Subjects of the bedrest study participated in 12 of the experiments to be performed on the LMS crew during the mission. By performing these investigations simultaneously on the ground, researchers hope to identify how one experiment is affected by another. The ground-based study added the benefit of optimal environmental controls and provided twice the research subjects as will be on the LMS mission. In addition, results of the study may have direct applications to people who have become more inactive on Earth.

NEUROSCIENCE EXPERIMENTS

One of the most common symptoms of adjusting to weightlessness is space adaptation syndrome, which affects approximately two-thirds of all astronauts and produces symptoms similar to motion sickness on Earth. Conflicting signals from an environment that suddenly has no "up" or "down" may produce confusion in the vestibular system, which is located in the inner ear and provides a sense of balance and bodily orientation. Pressure sensors in the muscles and skin also are involved, and the eyes contribute by sensing the body's relationship to other objects. In weightlessness, information sent to the brain from the inner ear and other sense organs no longer corresponds to the cues experienced in a 1-g environment. These conflicts may result in dizziness, headache, apathy, loss of appetite, and nausea. Although the malaise associated with space motion sickness disappears after a few days in space, the condition can cause a great deal of discomfort to the crew, may have an adverse affect on performance, and could be disabling in case of an emergency early in the mission.

Following return to Earth, the microgravity-adapted neurosensory system must readjust to a gravity environment. As a result, standing and walking, which require adequate balance, may be affected temporarily. The goals of the neuroscience investigations are to document the changes that occur in the neurovestibular system, to investigate the mechanisms involved in these changes, and to identify countermeasures to alleviate the effects of space motion sickness.

Torso Rotation Experiment (TRE)

Principal Investigator: Dr. Douglas Watt, McGill University, Montreal, Quebec, Canada

Co-Investigator: Prof. C.M. Oman, Massachusetts Institute of Technology, Cambridge, Massachusetts

The motor strategy of voluntarily fixing the head to the torso as if wearing a neck brace has been termed "torso rotation," since the upper body must turn to reposition the head. Continuous torso rotation on the ground usually leads to motion sickness, probably because of excessive suppression of the organs of balance, the vestibular system. A similar motor strategy is adopted by many individuals during spaceflight. Sometimes this is intended to combat motion sickness by reducing head movements, but often it precedes symptoms. If deliberate torso rotation on the ground causes motion sickness, inadvertent torso rotation in space should have the same effect. If symptoms are present already, the strategy could make them worse rather than alleviate the condition, but the delay may be such that the cause-effect relationship may not be noticed.

The goal of the TRE experiment is twofold: to monitor rotational movements of the eye, head, and upper torso in crewmembers as they perform routine activities and to determine if the normal pattern of eye/head/body coordination is changed as a result of prolonged exposure to weightlessness. A unit worn on the head holds electrodes that are placed near the eyes and a set of sensors that are attached to the head. The head unit is connected to a backpack that contains a computer for acquiring and storing data.

Ideally, the first set of in-flight data will be obtained before the onset of motion sickness symptoms. Subsequent data sets will be collected near the middle and end of the flight, and the astronauts will complete a motion sickness report before the end of each shift. A behavioral baseline will be established by data collection on Earth before and after the mission. Results will be analyzed postflight for evidence of torso-rotation-like motor strategies immediately after launch, with a possible return to more normal eye/head/body coordination as the mission progresses.

If inadvertent torso rotation is adopted by astronauts, they could be trained to avoid the practice. In addition, excessive vestibular suppression similar to that caused by torso rotation may be a major contributor to many kinds of motion sickness, including that experienced in cars, buses, planes, and boats. If so, this information may provide a new perspective on the problem and may suggest methods of preventing the disorder.

The Torso Rotation Experiment uses surface electrodes to record eye movements, a sensor package to monitor head rotations, and a second set of transducers mounted on the subject's back to detect upper body rotations. A microprocessor in the torso unit acquires all data and stores the information in removable modules.

Canal and Otolith Integration Studies (COIS)

Principal Investigator: Dr. Millard Reschke, NASA/JSC Space Biomedical Research Institute, Houston, Texas

Co-Investigators: Dr. Alain Berthoz, Centre National de la Recherche Scientifique (CNRS)/Collège de France, Paris France; Dr. Gilles Clément, CNRS, Toulouse, France; Dr. Bernard Cohen, Mount Sinai Medical Center, New York, New York; Dr. Makoto Igarashi, Nihon University, Tokyo, Japan; Dr. William H. Paloski, NASA/Johnson Space Center Space Biomedical Research Institute, Houston, Texas; Dr. Donald E. Parker, University of Washington, Seattle, Washington

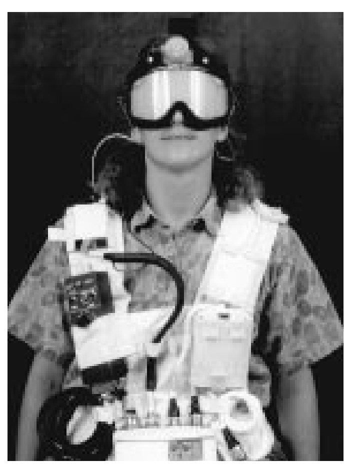
The knowledge of where our bodies are, relative to the environment, is a complex function involving the brain's ability to integrate information from virtually every sensory system, including the eyes and inner ear, as well as mechanically sensitive receptors in muscles and joints. The vestibular system, located in the inner ear, informs us about linear and angular accelerations we experience during head movements. To do this, our brain has to process information from two separate motion sensors in the inner ear, the semicircular canals and the otoliths, along with data from the other sensory systems. The semicircular canals sense angular (rotational) accelerations in three dimensions, and the otolith organs (containing both utricle and saccule, arranged approximately perpendicular to each other) detect transient linear accelerations in any direction as well as static changes in our orientation relative to gravity (tilt).

The integration of this information is used to control our eye movement and postural reflexes, two responses that depend on each other; for example, the information about head movement from the vestibular organ is used to stabilize eye position and to preserve vision during transient head movements. In the same way, information from the eyes about movement also is transmitted to the brain where it combines with vestibular information and contributes to the perception of body attitude and motion. The organization of this information is under adaptive control; thus, a person's expectations about sensory messages during voluntary movements are compared with the actual feedback from the sensory systems, constantly fine tuning further processing of the sensory information.

The COIS investigation is designed to study changes in the coordination of head and eye movements associated with adaptation to microgravity and to examine how vestibular and visual information is processed in the absence of a gravitational reference. The studies are divided into the Voluntary Head Movements (VHM) experiment and the Optokinetic Nystagmus (OKN) experiment.

Voluntary Head Movements: The VHM investigation will characterize how the coordination of head and eye movements change as a result of spaceflight. In the first experiment, scientists will study the interaction of eye movement responses as crewmembers voluntarily move their heads in a sinusoidal fashion (back and forth) while visually fixating on a stationary wall target or while attempting to fixate the target after the eyes have been blindfolded. In the second experiment, astronauts will track a target that is moving back and forth, first with the eyes only and then with both the head and eyes together. Since the eye movement responses in both experiments are frequency-dependent, all conditions will be tested using two sinusoidal stimuli: 0.3 hertz (Hz) and 1.0 Hz. In addition to response dependency on frequency, changes in canal-otolith interactions will be inferred by comparing responses during head movements in horizontal (yaw) and vertical (pitch) planes. Greater changes are expected in the pitch plane because head movements stimulate both the canals and otoliths on Earth.

Optokinetic Nystagmus: Although the vestibular system accurately detects motion during transient head rotations, it is less accurate during sustained rotation of both the body and head because of the mechanical properties of the semicircular canals. When we move our heads, however, the visual background also moves relative to our eyes and elicits another compensatory eye movement reflex called the optokinetic reflex. This reflex generates a characteristic eye movement called nystagmus, which consists of slow movements (following the visual background) alternating with corrective quick movements (saccades), which prevent the eye from moving too far in its socket and allow the subject to pick up new points of interest as the visual stimulus moves.



A subject wearing the optokinetic nystagmus apparatus during training. The head gear allows researchers to examine how vestibular, visual, and proprioreceptive inputs to the brain are integrated to provide appropriate information for spatial orientations in the absence of a gravitational reference.

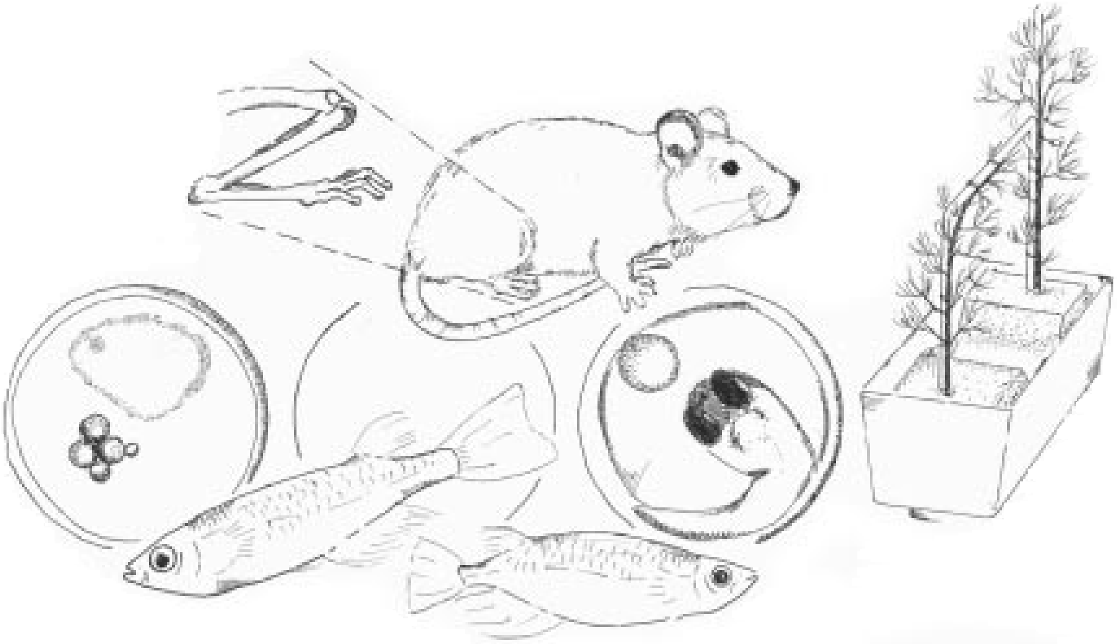
These optokinetic responses provide a visual input to the brain's simultaneous processing of visual and vestibular information and function to orient our eye movement responses gyroscopically in the proper plane relative to gravity. Normally, the axis about which the eyes move is aligned with the direction of gravity. If, however, both head and visual stimuli are tilted so that the visual scene is no longer aligned with gravity, the optokinetic response will be changed so that the resulting eye movements continue to be aligned with gravity and not the visual scene. This change in the axis of the eye movement to align with the gravitational reference is called cross-coupling, and changes in this response are the focus of the OKN experiments as the astronauts adapt to altered otolith input in weightlessness. Since the orientation of the OKN response on Earth is dependent on position (otolith information) with respect to gravity, changes in cross-coupling in space are predicted to shift from a gravitational to a bodily frame of reference.

Crewmembers will participate as test subjects and operators for both experiments, obtaining measurements early, midway, and late in the mission. While the adaptive changes typically lead to improved efficiency and reduction of space motion sickness during the flight, they are accompanied by perceptual and sensorimotor difficulty experienced during a return to Earth.

For that reason, both VHM and OKN experiments will be performed preflight to establish a defined Earth-stable baseline and postflight to track the recovery process. Repeated measurements will be made during the first week after the mission and will be compared to those obtained preflight.

Space Biology Discipline

ANIMAL ENCLOSURE MODULE EXPERIMENT



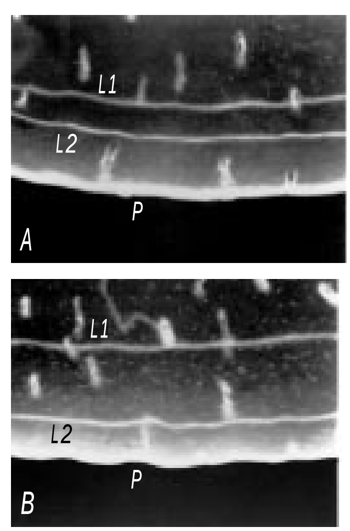
Biology experiments in space are necessary if scientists are to understand the changes in living systems that occur as a result of the microgravity environment. What happens to organisms when normal environmental influences such as gravity are removed? Can growth and development occur normally without such cues? Data from space biology research can lead to a better understanding of many of the basic mechanisms of both animal and plant physiology. From development and growth at the cellular level to the development and growth of entire organisms, the mechanisms that control various processes can be identified, studied, and perhaps eventually controlled.

Researchers on the LMS mission will conduct three experiments to provide answers to these and similar questions. The Animal Enclosure Module (AEM) will house laboratory rats for studies of bone loss, the Space Tissue Loss Module-Configuration B (STL-B) will allow observation of the embryonic development of fish, and the Plant Growth Facility (PGF) will support an investigation about the effects of microgravity on the cell walls of conifer seedlings. These experiments will contribute significantly to our basic understanding of the physiological processes in a microgravity environment, as well as to the current bank of biological and medical knowledge.

Animal Enclosure Module (AEM)

The Animal Enclosure Module is a self-contained habitat that provides its occupants with living space, food, water, ventilation, and lighting. Its internal waste management system guarantees that animals are isolated from their waste by-products and that these by-products and food crumbs do not escape into the open middeck where the crew is living.

The AEM is space-proven hardware. By the time of the LMS launch, it will have provided sustenance to its inhabitants during 17 previous missions. Twelve laboratory rodents will be passengers on the LMS mission. Six will be housed in each of two Animal Enclosure Modules in the orbiter middeck.



In these two photographs of rat leg bones, the inhibition of bone formation that occurs in space is evident. (A) is the tibia bone of a rodent that flew in space for 19.5 days, (B) is from a ground-based control rat, and (P) indicates the outer (periosteal) surface of the bone. The first tetracycline label (L1) of the bone-forming surfaces was administered to each rat the day before launch, while the second label (L2) was given the day after landing. The bone between the L1 and L2 labels formed during the flight. The flight rat formed much less bone than the ground-based control rat.

Role of Corticosteroids in Bone Loss During Spaceflight

Principal Investigator: Dr. Thomas J. Wronski, University of Florida, Gainesville, Florida

Co-Investigators: Dr. Bernard P. Halloran, Veteran's Administration Hospital and University of California at San Francisco, California; Dr. Scott C. Miller, University of Utah, Salt Lake City, Utah

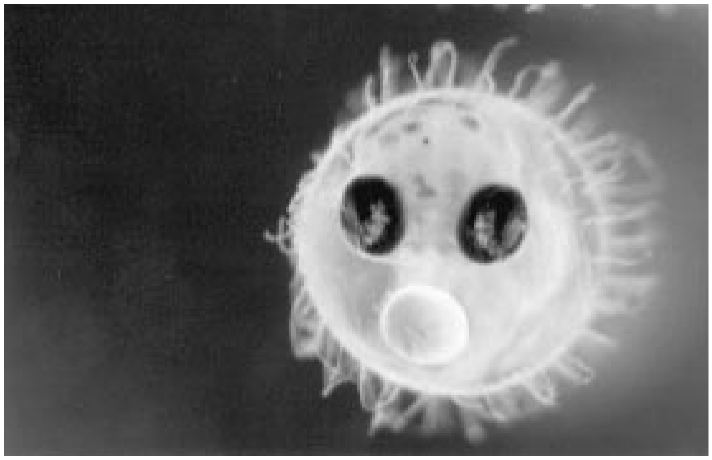
Corticosteroids are hormones produced by the cortex of the adrenal gland in response to stress, and their overabundance inhibits the growth of bones and leads to loss of bone mass. In-flight blood samples from astronauts and cosmonauts have revealed increased levels of plasma corticosteroids, particularly cortisol, raising the question of whether the production of excess corticosteroids in response to the stress of orbital flight may contribute to the human bone loss associated with space missions. A more complete understanding of the causes of bone loss in space may lead to more effective countermeasures during extended space travel.

Twenty-four male rats (12 flight and 12 ground-control) will be the subjects in this experiment. Before and after the mission, data will be gathered on their bone mass, levels of bone formation and resorption, and bone cell activity to determine the effects of spaceflight. Each rat will be injected before the mission with a calcein label that binds to the calcium on bone-forming surfaces. After the mission, scientists can determine how much bone growth has occurred by measuring the amount of bone deposited over the label.

Adrenal glands of laboratory rodents exposed to extended weightlessness have shown evidence of hypertrophy, an increase in size, which results in increased blood levels of corticosteroids. To eliminate the source of corticosteroids, six of the flight rats (three per AEM enclosure) will have had their adrenal glands removed a few days before launch. Then, these rats will be implanted with hormone pellets that will release normal levels of corticosteroids into their systems. The other six flight rats, with adrenal glands, are expected to experience adrenal enlargement during the flight and an increase in corticosteroid output. A control group of 12 rodents, 6 of which also have had adrenalectomies, will live in 2 identical Animal Enclosure Modules on the ground while LMS is in orbit.

During the mission, the crew will check the health of the rodents daily, viewing them through a clear window in the top of each module and noting their activity and general fitness. The crew also will resupply drinking water in each module.

After the mission, blood and bone samples from both intact and adrenalectomized rodents, both flight and ground populations, will be examined. Blood samples will be assayed for plasma corticosteroids, and bone samples will be studied to identify whether any skeletal abnormalities have developed in the flight rodents in the absence of corticosteroid excess.



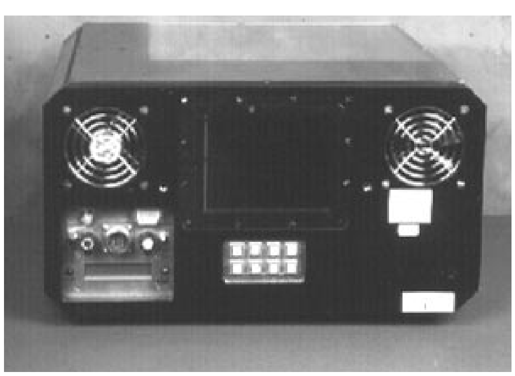
Development of Medaka *fish embryos is being studied during the LMS mission to determine if gravity is needed for normal embryogenesis.*

Space Tissue Loss Module - Configuration B (STL-B)

During embryonic development, a single cell divides into many cells, and those cells become specialized to form organs and function as a living system. As humans stay longer in space, it becomes increasingly important to understand the impact of microgravity on various stages of vertebrate embryogenesis. Determining these effects on vertebrate development will provide information about reproduction and differentiation in space and may provide vital clues as to how embryos on Earth use gravity as a developmental cue.

One of the goals of the STL project is to conduct ground-based, Shuttle middeck, and Spacelab studies on the impact of microgravity on biological systems at the cellular level of development. The ultimate objective is to understand the potential effects on human development, since all of our systems — including skeletal, muscular, and vestibular — develop under the influence of gravity. Researchers believe that gravity is critical to the maturation of these systems, and they wonder how each stage might be altered by the lack of gravity. Scientists also are interested in discovering if there are events in development that are initiated or cued by gravity. On LMS, researchers will be exploring the idea that embryonic growth, particularly neural development, is affected by gravity. This hypothesis will be examined by allowing fertilized fish embryos to develop in microgravity to determine whether the effects of gravity differ at certain stages of embryonic and post-natal growth.

STL-B provides a platform for microgravity experimentation that allows real-time interaction with on-going space experiments. The facility supports studies of mammalian cells, tissue cultures, and embryos and is easily modified to accommodate studies of fish, amphibians, plants, organic crystals, and other biotechnology research. The STL-B system includes a video microscope imaging system for real-time observation of experiments by scientists on the ground, allowing investigators to interact with operations to detect and induce cellular responses.



STL-B Facility

For LMS, the STL-B experiment activities are fully automated except for initialization, downlink television, and re-entry preparation. Using the video microscope imaging system, scientists will have direct video observation of developing fish embryos. The facility functions continuously from before launch until after landing, at which time, the STL-B will be powered down. The biological samples will be removed and returned to the Principal Investigator for processing.

Development of the Fish *Medaka* in Microgravity

Principal Investigator: Dr. Debra J. Wolgemuth, Columbia University College of Physicians and Surgeons, New York, New York

Co-Investigator: Dr. Carey R. Phillips, Bowdoin College, Brunswick, Maine

The LMS STL-B hardware will be used to test the hypothesis that gravity is required for normal embryo development. Investigators will conduct a systematic evaluation of vertebrate development and growth using the fish *Medaka* as a model. The *Medaka* is particularly suited to this experiment since it is a hardy fish whose embryos tolerate reduced temperatures well, allowing researchers to subject the embryos to low temperatures and slow embryonic development. This provides more time to study each stage of vertebrate development and maximizes the effects of microgravity on each stage. Also, the embryos are optically clear, which allows investigators to examine molecular markers visually and to follow the development of the internal organ systems with the STL-B video system.

Before the flight, baseline experiments will be conducted on Earth, where embryos will develop at reduced temperatures of 7 °C to 20 °C and will be compared to others that developed at normal temperatures of 24 °C to 28 °C.

Fixation of embryos will occur at different stages so that all phases of growth and development can be compared and studied. Rates of development for some key organs will be established before the mission, and molecular probes will be used to establish relationships between specific pattern-regulating genes and the development of specific organs. These studies will provide valuable data for selecting specific stages for study during flight.

About 2 hours after fertilization, approximately 6 *Medaka* embryos will be loaded into each of 6 optical chambers of the STL-B hardware. The embryos will be cooled to 14 °C, which will slow embryo development during preflight processing. Soon after the Shuttle achieves orbit, the temperature will be increased, allowing development to continue. At predetermined intervals during the mission, video microscopy will be downlinked to researchers on the ground. These downlinks are planned to observe key phases of *Medaka* development. Also, at specified intervals, embryos will be fixed (chemically preserved) for postflight evaluation.

A preliminary version of this experiment flew on STS-59, and another flew on STS-70, allowing researchers to evaluate the suitability of the STL-B for supporting development of the *Medaka* during spaceflight. Results of the STS-59 investigation suggest that the flight embryos may experience difficulty in establishing the extreme anterior structures, such as the eyes and the heart, and that the development of the heart may be delayed or abnormal. Preliminary observations of video downlink on flight day 4 showed that the heart wall appeared to be composed of thinner muscle tissue, and, in at least three cases, the initial heart tube did not fold to form the normal configuration. Embryos that were later cultured under similar media and temperature conditions on Earth did not exhibit these abnormalities. These preliminary observations support both the feasibility of real-time monitoring and the utility of the *Medaka* as a model for spaceflight studies.

LMS will offer a unique opportunity for the research team. In addition to increasing the number of specimens for examination, the longer flight will provide additional developmental data points for observation.

Plant Growth Facility (PGF)

Plants are an important part of our lives on Earth, providing food, shelter, and clothing and helping to maintain the composition of the air we breathe. For these same reasons, plants and their products will be critical to the health and well-being of people who will live and work in space.

The Plant Growth Facility supports whole-plant growth for 15 to 30 days under normal growing conditions. For LMS, the PGF will be located in the Space Shuttle's middeck and will house conifer (pine and Douglas fir) seedlings for study. Six Plant Growth Chambers are contained within the PGF facility. Seedlings will be maintained on agar nutrient medium blocks, eliminating the need for continual watering and feeding. A previous flight on STS-51 successfully tested this medium as a passive system for growing plants unattended.

This photo of Douglas fir seedlings in the Plant Growth Chambers shows the support structure for tree bending.

Lignin Formation and the Effects of Microgravity: A New Approach

Principal Investigator: Dr. Norman Lewis, Washington State University, Institute of Biological Chemistry, Pullman, Washington

Co-Investigators: Dr. Laurence B. Davin, Ms. Mi Chang, and Dr. Pieter Van Heerden, Washington State University, Institute of Biological Chemistry, Pullman, Washington

One important challenge facing biologists is that of establishing the way living organisms perceive and respond to gravity and how their cellular composition is affected by gravity. Plants are ideal specimens for studying such effects because they display significant and predictable responses.

The focus of the plant science experiment on the Life and Microgravity Spacelab mission is to establish the effect of the microgravity environment on the ability of plants to form a reinforcement tissue known as reaction wood. On Earth, woody plants produce this distinctive reinforcement tissue when their stems are bent contrary to their normal orientation. The reaction wood formation helps restore the stem to its upright position, which contributes to the plant's survival, but it has an adverse effect on wood quality and texture. Manufacturers of pulp, paper, and lumber products have a critical interest in our understanding of the biochemical and regulatory mechanisms that control reaction wood formation and in the development of ways to limit this type of tissue.

Conifer seedlings will be placed in the Plant Growth Facility in an orientation that favors reaction wood formation in Earth's gravity. The crew will perform a daily status check of PGF systems and will photograph the Plant Growth Chambers. Two of the six chambers will be opened for plant fixation, at which time the plants will be harvested and preserved chemically to stop their growth and development at predetermined intervals. Then, the plants will be frozen for postflight analysis. Electron and light microscopic study of the samples will define the time and place of reaction wood formation and the extent to which it forms. Chemical and biochemical analysis will complement the study, enabling scientists to measure the effects of microgravity on reaction wood formation and, if possible, to define the regulatory enzymes and genes involved. The technology used for this experiment will be incorporated into future space station facilities for plant growth.

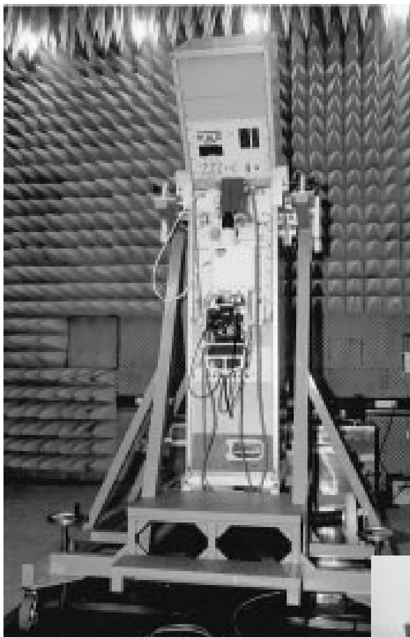
MICROGRAVITY SCIENCE

Dust settles gently onto a desktop, highlighted by a sunbeam through a window; a long fly ball arcs into center field; a glass-blower spins molten glass to keep it from sagging as it is shaped; and a child wonders at raindrops bouncing and splashing on the surface of a lake. The effect of the acceleration of gravity is such an accepted part of our lives that we rarely think about it.

These effects are not always desirable, however, especially during certain phases of materials processing. Mixers must operate almost constantly to keep ingredients uniformly blended; molten items must be cooled quickly or spun like the molten glass to prevent distortion of their external shape. Other products that depend on a well-ordered internal arrangement, such as protein crystals, are not as perfectly ordered as they could be because of gravity's effects.

Gravity also limits efforts to study the physical processes found in materials manufacturing and other technologies. For example, gravity is a driving force for convection (stirring) currents between hot and cold regions. These currents obscure other events that scientists wish to study and can affect the quality of the final product by causing it to be mixed improperly.

In the space environment, the masking forces of gravity are stripped away, and scientists can pursue research not possible on Earth. Average accelerations within a freefalling spacecraft orbiting Earth are approximately 1/1,000,000 the gravitational acceleration experienced at Earth's surface. The LMS microgravity science experiments will investigate many gravitational effects on the production and manipulation of certain materials. Scientists will study interacting fluid layers, stability of liquid bridges, and the behavior and properties of bubbles and drops of particular materials while they are suspended in a test chamber. In addition, they will investigate the melting and resolidification of solids to learn more about the effects of gravity on high-temperature processing methods. Protein crystal growth research, the goal of many experiments on previous Shuttle missions, will continue on LMS with the growth of approximately 90 protein samples. The results of all of these experiments will increase our understanding of the effects of gravity on fluid behavior, materials processing, and biotechnology. Conducting research in microgravity may eventually lead to improvements in both production methods and final products in Earth-based industry.

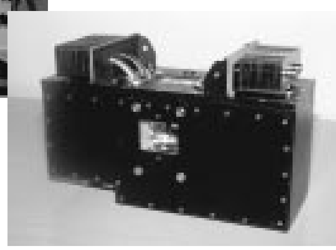


Bubble, Drop, and Particle Unit (BDPU), ESA Facility

Advances in materials processing have the potential to produce new high-strength metals and temperature-resistant glasses and ceramics for building everything from better electric power plants to future spacecraft. To advance such materials research, however, scientists need a better understanding of fluid processes that play a role in the production of most materials. Microgravity provides the opportunity for investigators to focus on such fundamental fluid processes.

One of the most important of these processes is the role of interfacial tension, the force created at the boundary (interface) of two immiscible phases (liquid/liquid, liquid/gas, or liquid/solid). This tension is the force that gives a soap bubble its characteristic spherical shape. The stronger and more uniform the surface tension of the bubble, the more stable and

The photo below shows a typical layout of one Test Cell Container and shows the observation window of the Liquid Cell.



uniformly spherical its shape will be. Interfacial tension typically decreases with increasing temperatures. As a result, vapor bubbles in a liquid usually will move toward the warmer part of the fluid, a transition called thermocapillary migration. Concentration variations also can have a dramatic effect on surface tension.

On Earth, the role of interfacial tension often is masked by other gravity-driven forces, such as buoyancy or sedimentation. In microgravity, however, the variation of interfacial tension generated along interfaces may create flows that can have profound effects on materials processing. The variations of surface tension are induced by differences in concentration or temperature. Investigations in this facility will help characterize interfacial processes involving either bubbles, drops, liquid columns, or liquid layers.

Since its first flight on the Second International Microgravity Laboratory (IML-2) mission in July of 1994, the BDPU has been upgraded to accommodate a high-voltage power supply so that experiments on electrohydrodynamic processes can be performed. The facility can accommodate several types of test cells with each one dedicated to a specific experiment. Commands can be sent from the ground to inject bubbles into liquid-filled test cells and then to subject these cells to predetermined temperature differences. Cameras and sensors will observe and record temperatures and densities as well as the positions of bubbles or drops.

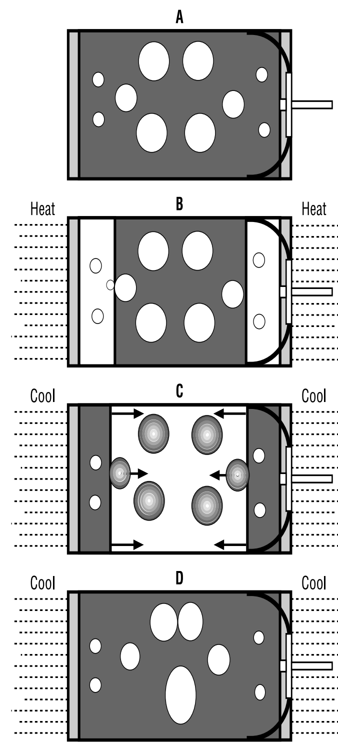
Four investigators will use the test cells to study how bubbles and drops react in liquids with varying temperatures and concentrations, how they interact with the solid/liquid interface during melting and solidification, and how convection is driven by differences in interfacial tension between adjoining liquid layers. The BDPU also will be used to perform fundamental investigations on the evaporation and condensation of bubbles and to study the effect of strong electric fields on the stability of liquid columns in microgravity.

Bubbles and Drops Interaction with Solidification Fronts

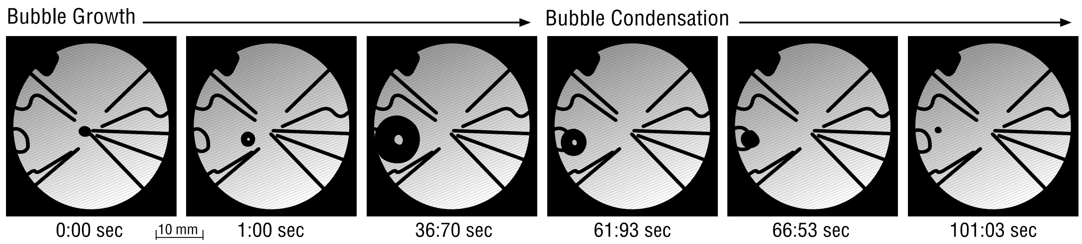
Principal Investigator: Dr. Rodolfo Monti, Dipartimento di Scienza e Ingegneria dello Spazio (DISIS), University of Naples, Italy

Co-Investigator: Dr. Raimondo Fortezza, Microgravity Advanced Research and Support (MARS) Center, Naples, Italy

As molten crystal and glass begin to solidify, bubbles may be formed by gas that is dissolved in the liquid matrix, causing imperfections in the final product. Also, components of molten alloys may be separated during melting or



For this experiment, pre-placed vapor bubbles in a solid material (A) will be studied as the material melts (B), as the molten material begins to cool (C), and after it has completely resolidified (D). Researchers will study the interaction between the vapor bubbles and the solid interface, as well as the movement of the bubbles within the liquid. Migration is generally from cold to hot parts of the fluid. Data gathered from this experiment will help investigators learn how to prevent bubbles in solidifying products or how to minimize the impact these bubbles have on the final product.



On Earth, vapor bubbles move so quickly because of buoyancy that they are extremely difficult to study. In microgravity, however, they should remain in place and even grow in size, allowing them to be studied. This sequence of photos was taken during the IML-2 mission and shows bubble growth and condensation over a period of 101.03 seconds.

solidification, forming bubbles or droplets in the alloy matrix. This investigation will provide new insight into better ways to prevent these flaws from occurring in metals and alloys as they are produced in the microgravity environment.

The test sample will be a solid matrix of tetracosane, a material that is transparent in the liquid state and that melts at low temperatures. In addition, the sample has a surface tension in the liquid state that does not change significantly in the temperature range near the melting point, ensuring that bubbles will not be affected significantly by thermocapillary (Marangoni) movement. The matrix will include pre-formed air bubbles of different sizes. The tetracosane will be heated above its melting point of 55 °C. As the melting front reaches the bubbles, they will be released and any motion will be observed. The locations and dimensions of the bubbles will be studied and documented along with other characteristics of the migration.

When the solid is melted completely, the test cell walls will be cooled, and a new solidification process will take place, during which the interaction of the migrating bubbles with the solidification front will be studied. A similar experiment flown on the IML-2 mission seemed to show, as expected, an absence of thermocapillary migration near the solidification front, guaranteeing the interaction with an advancing solidification front.

In the second part of the experiment, water drops of different diameters will be injected into a liquid matrix to study drop behavior. Changing the temperature and heat flux on the walls of the container will cause changes in the positioning of the liquid/solid interface, providing information on the way droplets are captured by (or pushed away from) a moving solidification front.

Evaporation and Condensation Kinetics at a Liquid Vapor Interface

Efficient Cooling of High Powered Small Electronic Devices by Boiling Under Microgravity

Principal Investigator:
Dr. Johannes Straub, Technische Universität München, Munich, Germany

Co-Investigator: Dr. Herman Merte, Jr., University of Michigan, Ann Arbor, Michigan

The prime objective of the first study is to investigate the kinetics of evaporation and condensation at liquid/vapor interfaces to gain a better understanding of the fundamentals of these processes. These mechanisms occur in the natural environment by evaporation on seas, lakes, and rivers and by condensation in clouds. They also are applied in many technical operations where liquid/vapor interfaces are not in equilibrium, such as boiling and condensation, to determine the interfacial heat and mass transfer.

This experiment is a reflight of an experiment flown on the IML-2 mission and is a further investigation of the kinetics of evaporation and condensation at the phase interface of a single vapor bubble in a homogeneous liquid. The test liquid is an alternative refrigerant (R123), which allows higher pressures and temperatures than the refrigerant used in the IML-2 experiment. R123 is brought to a supersaturated state by reducing the pressure below its saturation pressure. A vapor bubble is generated by a short heating pulse with a spot heater in the liquid. The vaporization is studied at several temperatures between ambient and 120 °C and between pressures of approximately 1 to 14 times normal atmospheric pressure. Because of buoyancy in Earth's gravity, vapor bubbles disappear very rapidly from the field of view. In microgravity, however, a vapor bubble will remain where it nucleates and will grow in size; thus, its growth can be observed and evaluated with respect to time.

The same test container is used for a second study to investigate the fundamentals of boiling heat transfer on small heating elements of differing shapes and sizes. Since boiling is a very efficient method of heat exchange, it is used in many energy conversion systems, which will benefit from detailed advanced research in this field. For example, boiling can be used to cool small, high-powered electronic devices, such as computer chips or micro-energy converters.

Preliminary experiments conducted on the IML-2 mission disclosed various mechanisms of boiling heat transfer and indicated that boiling behavior differs according to the rate of heating and the condition of the fluid, as defined by its properties. Advanced hardware will be used to observe and measure the experiment during the LMS mission, combining the use of optical and electronic systems. Investigators will attempt to determine the conditions at nucleation and to optimize heat transfer. Different heater shapes and sizes will be used to determine their influence on boiling mechanisms. In addition, the influence of a dissolved inert gas on the boiling process and on the relationship between the heater surface temperature and the heat transfer rate will be investigated.

The Electrohydrodynamics of Liquid Bridges

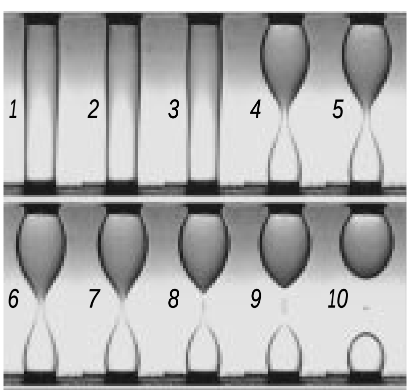
Principal Investigator: Dr. Dudley Saville, Princeton University, Princeton, New Jersey

A liquid thread, such as a thin stream of water coming out of a faucet or the column of water created between two wet fingers, breaks up into small drops because of the action of both surface tension (capillary instability) and gravity. An axial electric field (an electric field aligned along the long axis of a liquid thread) can stabilize the thread against such destabilizing forces. This is an electrohydrodynamic phenomenon that is important in industrial applications such as ink-jet printing and polymer fiber spinning.

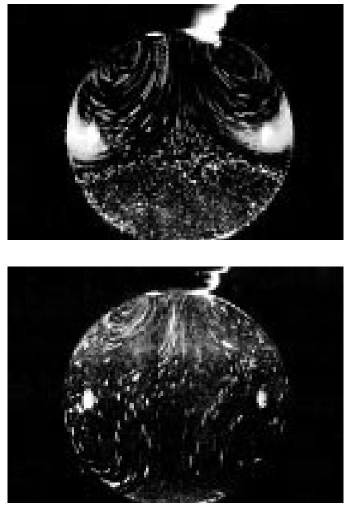
This investigation will provide information about the stability characteristics of columns of dielectric fluid (liquid that barely conducts electricity) when they are deployed in another immiscible liquid or in air. Fluids to be studied include castor oil, clove oil, eugenol, and silicone oil. When these experiments are conducted on Earth, it is necessary to use a density-matched fluid surrounding the liquid column to study the effects of electric fields on capillary instabilities, making it impossible to perform such experiments with liquid/gas systems in ground-based laboratories. Also, electrohydrodynamic experiments are complicated by the transfer of electrical charge between the two fluids along the liquid/liquid interface. The microgravity environment allows investigators to use a wider range of fluid densities and viscosities, and the liquid/gas combination provides a boundary free of electrical charge, which simplifies analysis. Terrestrial density-matched studies also can be carried out to provide data for comparison with similar flight experiments.

This experiment will focus on the series of shape changes that occur in a fluid bridge suspended between two electrodes. By applying direct or alternating current electrical fields, scientists can study the transition of the bridge from a cylindrical shape to a vase-like shape, followed by "pinch-off" as the applied electric field is stepped down or cut off abruptly. In the step-down mode, new stable configurations are reached for each voltage level. The cylinder will evolve through a series of increasingly vase-like shapes until pinch-off occurs. From this process, investigators can learn how much electrical field strength is needed to stabilize fluid cylinders against the action of interfacial tension in the absence of gravity.

Although the intent of the experiment is to improve the fundamental understanding of electrohydrodynamics with respect to liquid columns, similar experiments have been conducted with liquid drops. There are several important potential applications for such knowledge, including atomization and spraying, droplet coalescence, polymer blend morphology, polymer membrane manufacturing, and fiber spinning.



This sequential photograph, taken in a ground-based laboratory, shows an initially stable density-matched castor oil/eugenol liquid bridge deployed in silicone oil. Typically, 1 Kilovolt (kV) per centimeter (cm) was used to stabilize the cylinders. After the voltage is abruptly cut off (photo 3), the interfacial tension dominates and renders the fluid bridge unstable. The initial deviation from a cylindrical shape, the subsequent increasingly vase-like shape, and eventual pinch-off can be seen.



Time-lapse photography shows a liquid drop containing suspended tracer particles. The motion of the tracer particles is caused by surface tension convection.

Nonlinear Surface Tension Driven Bubble Migration

Principal Investigator: Dr. Antonio Viviani, Seconda Università di Napoli, Aversa, Italy

This experiment continues investigations into the motion of bubbles immersed in a liquid with an uneven temperature distribution. The motion of the gas particles is driven by variations in the surface tension along the boundary between the liquid and the injected bubbles. These variations are created by the temperature dependence of the surface tension. The study of the phenomenon has applications for many aspects of materials processing in space, such as the degassing of liquified matter before solidification to produce better and stronger metals, alloys, glasses, and ceramics.

This research can be conducted only in a microgravity environment because Earth's gravitational field acts on density differences between gases and liquids, making buoyancy forces predominant. These forces mask the motion of bubbles caused by variations of the surface tension along the surface of each bubble. Investigations on IML-2 showed the first evidence of thermocapillary bubble migration with the bubbles moving from hot liquid to cold, a reversal of classical migration, in which bubbles move from cold liquid to hot. This phenomenon was predicted by the investigator and resulted from the unusual property of the liquid — the surface tension of the bubbles decreased with decreasing temperature through a specific temperature range.

On the LMS mission, air bubbles will be injected into an aqueous solution (water and long-chain alcohol) under a thermal gradient (hot on one end, cold on the other). Investigators will determine the non-uniform velocity of the injected bubbles and will attempt to stop them in certain positions by varying the temperature gradients. The experiment will be repeated with several bubbles of different dimensions (2 to 12 millimeters in diameter) and under different thermal gradients to understand better the phenomenon and correlation laws of the migration speed in terms of bubble radius and temperature difference. Images of the bubble migration will be downlinked to investigators, who will control the experiment from the ground.

Oscillatory Marangoni Instability

Principal Investigator: Dr. Jean-Claude Legros, Microgravity Research Center, Free University of Brussels, Belgium

Co-Investigators: Dr. Philippe Géoris, Microgravity Research Center, Free University of Brussels, Belgium;
Dr. Bernard Roux, Institute of Fluid Mechanics of Marseille, France;
Professor Manuel Velarde, Universitad Complutense de Madrid, Spain

Many manufacturing processes depend on melting and resolidification to create a final product, such as a metallic alloy or a single crystal for use in electronics. Often, however, the individual components will separate into individual layers while in the liquid state. As the temperature changes, surface tension driven convection (Marangoni convection) creates flows within and between these layers that can be regular or that can oscillate in a highly irregular manner, depending on the temperature gradients involved. Understanding this process and the temperatures at which convection starts and at which the flows become irregular is of importance for all manufacturing that involves the liquid state of matter.

This experiment will use the BDPU to gather data that will allow scientists to model these flows accurately. A similar experiment was flown on the IML-2 mission, using silicone oil sandwiched between layers of the liquid fluorinert™. In this experiment, stationary convection was observed. For LMS, a fluid layer of methanol will be sandwiched between two layers of n-octane, an immiscible fluid, and will be subjected to a temperature gradient. Using cine film, video cameras, and thermistors, investigators will study convective flows starting in each layer to determine the critical temperature difference between the layers where convection starts, to observe the development of flow patterns that are stable over a period of time, and to identify the point where the stable flow transitions to an unstable flow. Scientists also plan to determine the velocity field within the liquids, the frequency at which the flows oscillate as a function of the temperature differences between the layers, and the three-dimensional flow pattern of the three liquids.

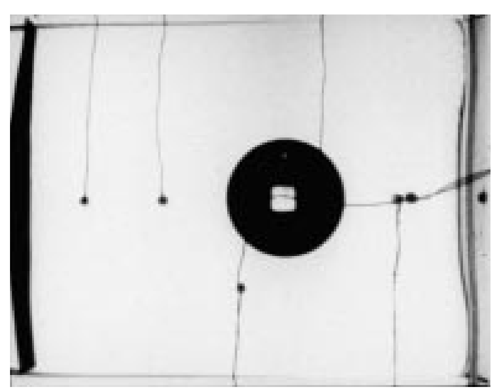
Thermocapillary Migration and Interactions of Bubbles and Drops

Principal Investigator: Dr. R. S. Subramanian, Clarkson University, Potsdam, New York

Co-Investigators: Dr. R. Balasubramaniam, NASA/Lewis Research Center, Cleveland, Ohio; Dr. Günter Wozniak, Bergakademie Freiberg, Germany

Bubbles and drops are encountered in the formation of alloys and in various other materials processing applications, such as solidification. It is important, therefore, to develop a scientific understanding of the behavior of these objects and to learn to manipulate them in low gravity where buoyant rise will be of negligible consequence. In long-duration space missions, for example, recycling of waste material will be essential, and separation processes used for this purpose might involve bubbles and drops.

In this experiment, the movement of bubbles and drops in a liquid under the action of a temperature gradient will be studied. Temperature gradients cause varia-



IML-2 investigators gathered data primarily on the motion of single bubbles or drops in a temperature gradient, such as this air bubble in silicone oil. Investigations on LMS will help expand these data by providing information on the interactions between pairs of drops and pairs of bubbles.

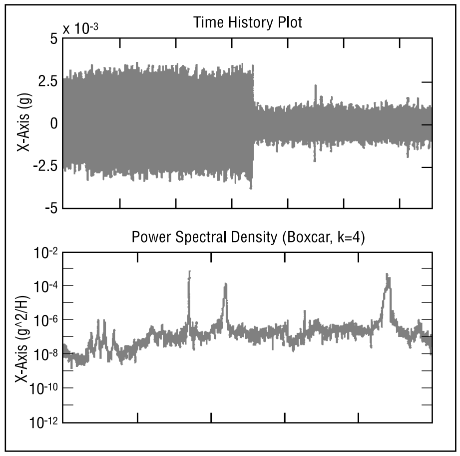
tions in the interfacial tension on the surface of the bubble or drop; on Earth, these gradients usually propel the bubble in the direction of warmer liquid. In experiments on IML-2, data were obtained on the motion of a single bubble or a single drop in a temperature gradient; in this follow-on study, the focus will be on interactions between pairs of bubbles and pairs of drops. Such interactions are important in determining whether two bubbles will approach each other or will recede from each other as they move in the temperature gradient. Selected experiments also will be performed on isolated bubbles, and tracer particles will track the motion of the liquid surrounding the bubble.

Up to 6 series of test runs will be conducted, each lasting about 4 hours. In each series, a temperature gradient between 0.1 and 1.0 Kelvin (K)/millimeter will be established in the test fluid. Approximately 6 to 10 pairs of bubbles or drops will be injected, one pair at a time, and investigators on the ground will monitor the motion through downlinked video. Selected runs will be recorded on cine film. At the end of the migration process, the bubbles will be extracted before a new pair is injected. Results from the experiments on bubble velocities, shapes, and flow patterns will be compared with theoretical predictions where appropriate.

ACCELEROMETERS – CHARACTERIZING THE MICROGRAVITY ENVIRONMENT

Microgravity science investigations require a stable, low-gravity environment to yield the most accurate data. Vibrations caused by on-board activity and by the operation of pumps, thrusters, fans, and cameras in the orbiter also can impact the quality of the research.

The LMS payload includes three instruments designed to measure these low-level accelerations and vibrations aboard the Space Shuttle: the Microgravity Measurement Assembly (MMA), the Orbital Acceleration Research Experiment (OARE), and the Space Acceleration Measurement System (SAMS). These systems collect data about small disturbances to the microgravity environment, providing investigators with insight into conditions that might affect the results of their experiments. All three have flown in space before, affording investigators the opportunity to analyze the microgravity environment in the Space Shuttle over the course of a mission. This information also has helped hardware developers to refine their instruments, isolating the experiments as much as possible from minor disturbances aboard the Space Shuttle.



These plots of SAMS data from the Spacelab-J mission show examples of typical vibrations produced by equipment operations on Spacelab. The abrupt drop in acceleration approximately 70 seconds into the time history plot indicates a decrease in vibrational level when the Life Sciences Laboratory Equipment (LSLE) refrigerator/freezer compressor cycled off. In the corresponding power spectral density plot, the peaks at about 22 and 44 Hz represent the frequencies excited by the LSLE. The sharp linear peak at 17 Hz is related to the dither of the Ku-band antenna. Lower peaks below 10 Hz are associated with orbiter structural frequencies.

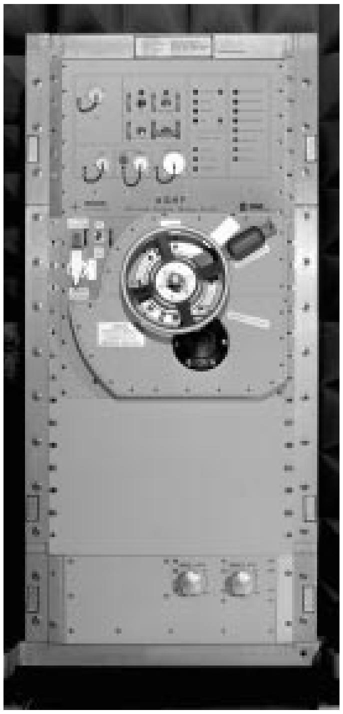
The MMA is a microgravity monitoring system capable of providing real-time display of accelerations detected by three sensor heads. Most of the MMA sensors can detect accelerations in the 0.1- to 100-Hz range. One sensor, called the Accéléromètre Spatial Triaxial Electrostatique (ASTRE) measures accelerations below 0.1 Hz. The ASTRE working principle is based on keeping a proof-mass motionless in a fixed position and attitude by electrostatic suspension. By measuring the strength of the electrostatic force that is required to keep the proof-mass stationary, scientists can measure the acceleration levels in three dimensions. The analog data from the sensors are routed to the instrument's central Microgravity Measurement Electronics computer for processing, formatting, and downloading. The real-time analysis of the data enables scientists on the ground to have an immediate assessment of the microgravity environment and to plan for possible corrective actions on their experiments.

The OARE instrument houses a proof-mass suspended in an electrostatic field. The proof-mass is sensitive to minute changes in acceleration caused by Earth's gravity, centripetal force, and atmospheric drag. The unit's electronics will record the effects of these small changes in the range from steady accelerations to 0.01 Hz in the Space Shuttle environment.

The SAMS sensors detect accelerations in the 0.01- to 10-Hz or the 0.01- to 25-Hz range with three 3-axis acceleration sensor heads. Each sensor head consists of a proof-mass suspended by a quartz element, allowing movement along one axis only. A coil is attached to the mass, and the assembly is placed in a magnetic field. Accelerations move the mass from its rest position, altering the magnetic field and causing current to flow in an electrical circuit. The current is proportional to the acceleration magnitude. The sensor signals are digitized by the SAMS unit and are recorded on optical disks.

OARE is located outside the Spacelab in the orbiter's payload bay, while the MMA and SAMS instruments have remote sensor heads located on Spacelab Racks 3, 7, and 8 for detection of accelerations affecting the microgravity science experiments housed in those hardware racks. Once activated, each of these accelerometers will monitor the Spacelab environment continuously, providing real-time and postflight data to the investigators and hardware developers.

After the flight, the microgravity acceleration data from MMA, OARE, and SAMS will be analyzed and a report will be prepared, summarizing the LMS microgravity environment. The report will help the Principal Investigators analyze science data gathered during the mission.



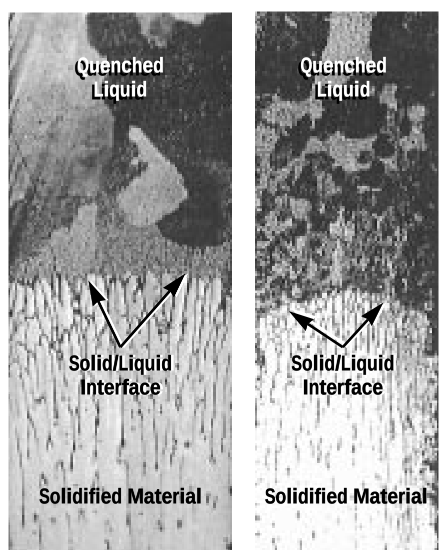
Advanced Gradient Heating Facility (AGHF), ESA

Manufacturing processes on Earth must take into account the pervasiveness of gravity, since not all of the effects caused by gravity are desirable; some cause products to mix unevenly, resulting in a disorderly internal structure. Uniform mixing and composition determine such factors as strength and brittleness. For example, semiconductors, the basis for modern electronics, depend on the precise mixing of components and on a highly ordered structure to produce single crystals. (In an individual crystal, constituent atoms line up on a single set of geometric planes.) While it is possible to grow near-perfect single crystals of silicon and some other materials, advanced semiconductor materials often have multiple flaws when produced on Earth.

In the microgravity environment available on the Space Shuttle and future orbital platforms, many of these gravity-induced imperfections can be eliminated. On Earth, the major source of heat and mass motion during solidification is usually gravity-driven fluid flows (buoyant convection). In space, the random motions of individual molecules (diffusion) may dominate.

The AGHF supports the production of advanced semiconductor materials and alloys using the directional solidification process, which depends on establishing a hot side and a cold side in the sample (a temperature gradient). It provides an extremely stable temperature environment of up to 1,400 °C, high-temperature gradients of up to 100 °C/cm in the solidification zone, slow movement of the gradient across a sample to provide slow growth rates, efficient cooling through the use of a liquid metal cooling ring attached to the sample container, and Peltier pulse marking capability. The AGHF consists of three modules mounted in one side of a Spacelab double rack: the Core Facility Module contains the processing chamber with the furnace inside; the Electronics Module contains the controls and equipment necessary to operate the furnace; and the Gas Storage Module contains argon for chamber repressurization and sample cooling.

Growth rate is an important parameter in the production of many materials, yet the solidification rate often is different from the rate of movement of the sample cartridge in the furnace. To help determine the actual growth rate, the AGHF includes a Peltier pulse marking capability that sends a pulse of electrical current through the sample at specific times to mark the internal structure in the solid/liquid interface along the electric field. Demarcation occurs as a result of heating caused by the resistance encountered by the current as it moves across the interface between the liquid and solid states. By examining cross-sections of the crystal, scientists can locate these marks and determine the precise growth rate for each portion of the experiment as well as the three-dimensional shape of the solid/liquid interface at the time of the pulse. A precise understanding of these factors will improve the general knowledge of the physical phenomena involved in the solidification process, improving materials processing on Earth and future semiconductor and materials processing research in space.



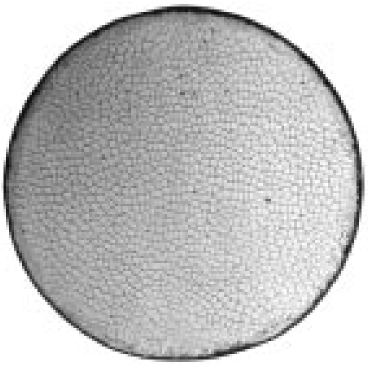
These longitudinal sections of identical samples processed in microgravity (left) and on Earth (right) show the variation in microstructure spacing that results from the different processing environments.

Comparative Study of Cells and Dendrites During Directional Solidification of a Binary Aluminum Alloy at 1-g and Under Microgravity

Principal Investigator:
Dr. Henri Nguyen Thi, University of Aix-Marseille, France

Co-Investigators: Dr. Bernard Billia, University of Aix-Marseille, France; Dr. Denis Camel, Dr. Béatrice Drevet, and Dr. Jean-Jacques Favier, Commissariat l'Énergie Atomique (CEA), Grenoble, France

The final properties of alloys and semiconductor crystals depend strongly on the internal microstructure formed during processing. In an ideal environment, three factors control the structure formed during directional solidification processing: the initial concentration of the solute, which is the chemical component that is mixed into a larger amount of another component (the solvent); the temperature gradient at the solid/liquid interface; and the rate at which the temperature gradient is moved across the sample (the pulling rate). If the first two factors are constant, the shape of crystal growth in the interface between the solid and liquid portions of the sample changes as the temperature gradient moves at different speeds. At slow growth speeds, the shape of the interface and the resulting growth is



By carefully cutting, polishing, and etching a series of transverse samples, like the one pictured, scientists can determine the precise form and structure of the solid/liquid interface.

nearly flat (planar). As the rate of movement of the temperature gradient is increased, the interface region forms a cellular structure. At high rates of movement, the cellular shapes take on dendritic, or tree-like, structures.

On Earth, this process is strongly affected by gravity-induced convection flows in the liquid portion of the sample. In microgravity, diffusive transport phenomena (which are masked by gravity in Earth-based operations) control the process. Convective flows and diffusive transport define both the point at which the shape transitions take place and the characteristics of the cellular or dendritic patterns that are formed. These characteristics determine the properties of the sample and include the spacing, as well as the radius and length of the cells or dendrites and the distribution of the solute in the alloy (a condition known as microsegregation).

Although much study has been conducted on Earth about the precise conditions at which shape transitions occur and about the factors affecting the formation and selection of the cellular or dendritic patterns, many questions remain. The purpose of this experiment is to examine cellular and dendritic formations under conditions in which convection is minimized and diffusive phenomena are dominant, allowing scientists to understand better the influence of convection on these processes. From the data, the investigators will develop an improved model of the cell-dendrite transition process that includes explanations for diffusive and convective conditions.

The experiment will process two samples of an aluminum alloy. After each sample is melted and thermally stabilized, controlled solidification will begin with a precise growth rate. After the furnace has moved 80 millimeters over the sample, it will be quenched (rapidly cooled), freezing the shape of the solidification front. During the LMS mission, two runs will be carried out with the same alloy composition and thermal gradient but with two different velocities. After the mission, these samples will be cut and polished so that investigators can determine the characteristics of the microstructure. By superimposing these data over theoretical projections, a more adequate model of the transition process can be developed for diffusive flows.

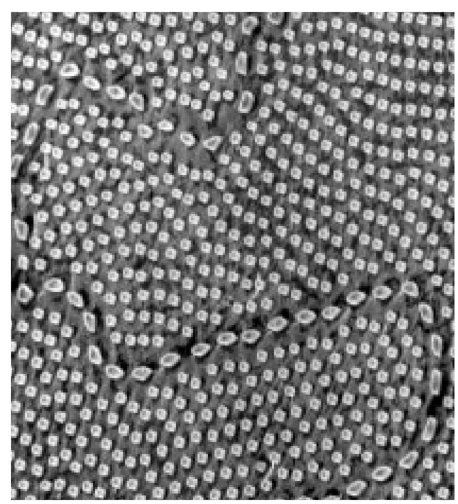
Coupled Growth in Hypermonotectics

Principal Investigator: Dr. Barry Andrews, University of Alabama at Birmingham, Alabama

Co-Investigator: Dr. Sam Coriell, National Institute of Standards and Technology, Gaithersburg, Maryland

Scientists are interested in a number of alloys that cannot be easily produced on Earth, because the components are immiscible and separate like oil and vinegar during processing. As a result, these alloys are poorly understood and difficult to process, limiting their use in engineering, chemical, and electronic applications. If the internal structures of these unique materials could be controlled during solidification, immiscible alloys could be extremely useful for specialized applications. On Earth, however, convection and sedimentation hinder the study of their solidification.

This experiment will process samples composed of aluminum and indium (AlIn) in the AGHF using the directional solidification method. The focus is on maintaining a planar solidification front in the alloy as it solidifies so that the final product consists of uniformly distributed and aligned indium fibers in an aluminum matrix. Investigators have selected the exact chemical composition of the alloy very carefully and will use an appropriate temperature gradient and a slow growth rate to ensure the even distribution of the fibers. Crucible materials were chosen to minimize interaction between the crucible and the alloy. The processing of the AlIn samples will push the limits of the AGHF's capabilities, with a temperature gradient approaching 100 °C/cm and a growth rate of 1 micrometer per second. After the mission, the investigators will cut and etch sections of the samples to study their microstructure. Chemical analysis will determine if a uniform composition was obtained. Results will be used to verify or modify a theoretical model to predict specific details of the solidification process, such as interfiber spacing, fiber diameter, and the percent of volume occupied by the fibers.



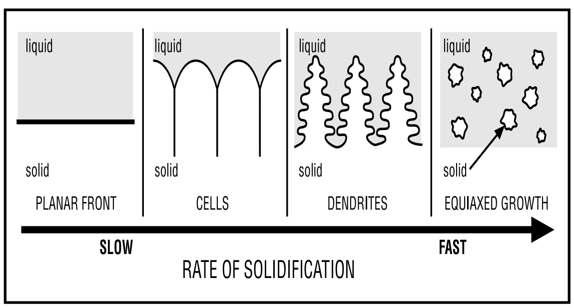
This photomicrograph shows fibers of indium in an aluminum matrix. The sample was processed during low-gravity parabolic maneuvers on the KC-135. Experiments on LMS may provide a more uniform alignment of the fibers and will contribute to current knowledge about processing immiscible alloys in microgravity.

STATES AND TRANSITIONS

Everyday, we experience materials in the four basic states of matter: solid, liquid, vapor, and plasma. The tables on which we eat are comfortingly solid and stable, the water we drink is a refreshing liquid, steam from vaporized water helps us iron clothes, and the plasma in fluorescent bulbs lights the areas in which we work. Materials move between the four states as energy is put into or taken out of the particular material. If we take energy out of water, it freezes and becomes solid ice; if we add energy to it, it boils and becomes vapor, which we know as steam.

Energy must be added to many raw materials before they can be processed, changing them from a solid state to a liquid. To achieve the desired properties in the final products, the liquid material must be cooled in a controlled manner until it once again becomes a solid. In this process, the liquid material gives off energy from the surface of the area where solidification is occurring. The rate at which this energy is dissipated determines much about the internal structure of the final material.

If the material is solidified at a slow, steady rate, it gives off energy in a slow, even manner from the solid surface that is forming and produces a well-ordered structure based on the properties of the material. For example, in the growth of semiconductor crystals, slow, controlled solidification can produce a single large crystal of the particular material. In this case, the solidifying surface is nearly flat, or planar. If, however, the material is solidified faster, it must give off more energy in a shorter amount of time. A larger surface area is needed from which to dissipate energy, so finger-like appendages called cells grow to increase the surface area. If the rate of solidification continues to increase, these cells grow appendages to increase the surface area further. The resulting tree-like structures are called dendrites. The spacing within the cells and dendrites also is determined by the rate of solidification. The faster the rate of solidification, the closer together the cells or dendrites and dendrite arms will be. At very fast rates, the solidification surface breaks up into discontinuous pieces. Solid particles form, or nucleate, in the liquid, producing equiaxed dendritic growth.



This diagram shows the correlation between the rate at which the solid/liquid interface moves across a sample and the shape of the resulting microstructure.

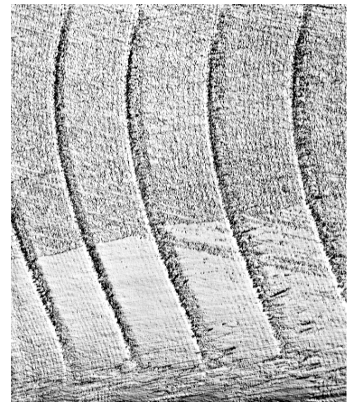
Scientists seek to understand the conditions at which freezing materials transition from flat (planar) steady growth, to cellular growth, to dendritic growth. They also want to determine the factors affecting these transitions. A better understanding of the transitions will help researchers achieve the precise microstructure that is desired in a material. In the microgravity environment of Spacelab, scientists can study these transitions in ways that are not possible on Earth, improving our understanding of materials processing in both environments.

Effects of Convection on Interface Curvature During Growth of Concentrated Ternary Compounds

Principal Investigator:
Dr. Thierry Duffar, CEA, Grenoble, France

Co-Investigators: Dr. Ernesto Dieguez, CEA, Universidad Autonoma de Madrid, Spain; Dr. Jean Paul Garandet, CEA, Grenoble, France

During the solidification of metallic or semiconductor alloys, diffusion, convection, and the motion of the solid/liquid interface can cause the individual components of the alloy to separate from one another, or segregate, resulting in a non-uniform (inhomogeneous) sample. This condition, created as solid material forms from a liquid in a temperature gradient, is called a chemical segregation and is not desirable since the properties of an alloy depend on a uniform mixing of the components and a precise, well-ordered structure. Studies of the processes involved with chemical segregations are hampered by convective flows, which mask the diffusive flows, and by the fact that the solid/liquid interface is not a perfectly flat front, but rather a three-dimensional curved shape that also is affected by gravity.



The figure above is a solid indium-antimonide sample that has been subjected to Peltier pulsing during solidification. A series of 50-ampere, 3-second pulses were sent through the material at a rate of 1 per minute, visibly altering the structure of the solidifying material. This change in appearance results from the heating caused by the resistance encountered by the current as it moves across the interface between the liquid and solid states. Investigators determine the shape, location, and rate of movement of the liquid/solid interface during processing by matching the time of the Peltier pulse with the resultant demarcation in the ingot.

This experiment will use Bridgman growth techniques specifically to investigate segregation in ternary (three-component) compounds. This radial segregation is caused by the curvature of the solid/liquid interface in the presence of diffusion and the absence of convection. The curvature is very sensitive to both diffusion and convection, especially in highly concentrated samples like the ternary compounds chosen for this experiment; therefore, the exact levels of gravitational forces will be a major factor, and scientists will examine data on accelerations to determine effects on crystal growth and segregation.

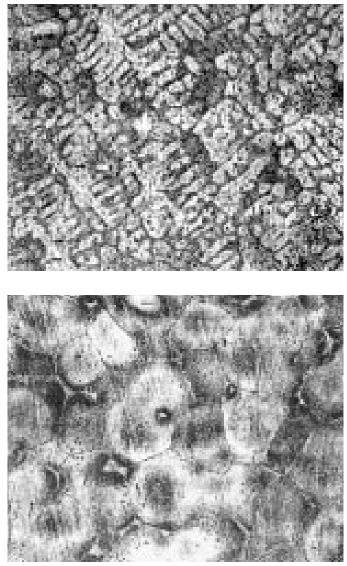
For this experiment, a polycrystalline ingot of gallium-indium-antimony (GaInSb) will be melted and resolidified, with the AGHF in its high thermal gradient mode. A crucible of variable thermal conductivity and roughness will be used to control the interface curvature, and Peltier pulses will be used to mark the interface. This demarcation will allow scientists to determine the interface curvature and the solute distribution in the sample during post-flight analysis.

Equiaxed Solidification of Aluminum Alloy

Principal Investigator: Dr. Denis Camel, CEA, Grenoble, France

Co-Investigators: Dr. Marie-Danièle Dupouy and Dr. Jean-Jacques Favier, CEA, Grenoble, France

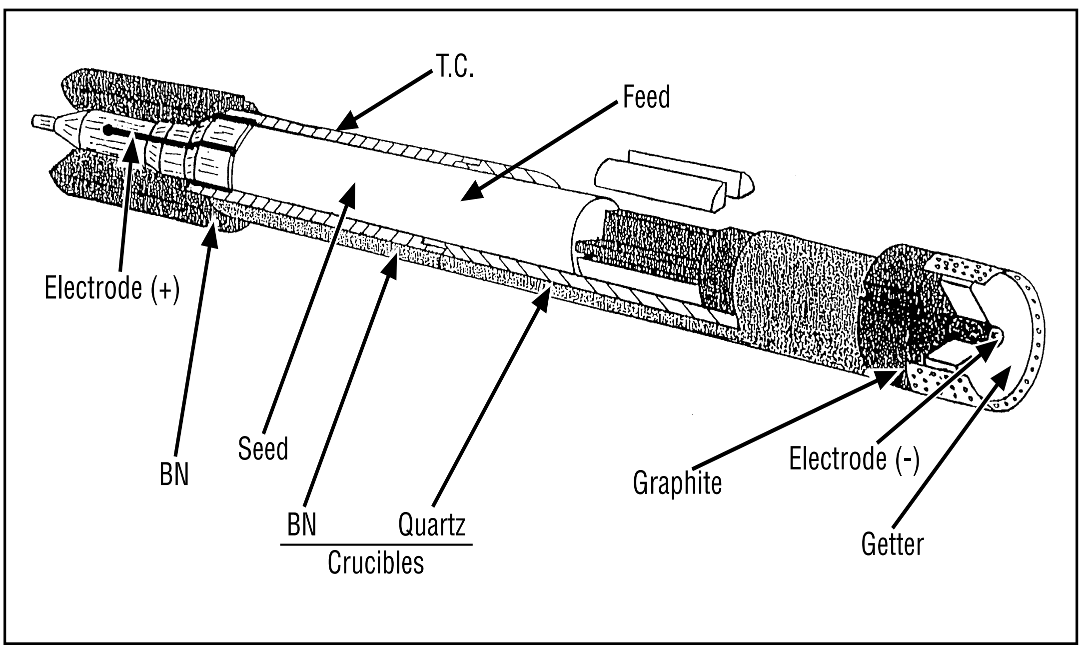
The solidification of alloys occurs in one of two ways: either in columnar fashion along the direction of the movement of the thermal gradient, resulting in long column-like grains, or in equiaxed fashion, which starts from a nucleus in the liquid material and results in spherical grains with no particular alignment. The transition from one type of structure to the other depends on the thermal conditions, the presence and characteristics of nuclei in the liquid material, and the convection that moves the nuclei and the equiaxed grains inside the liquid portion.



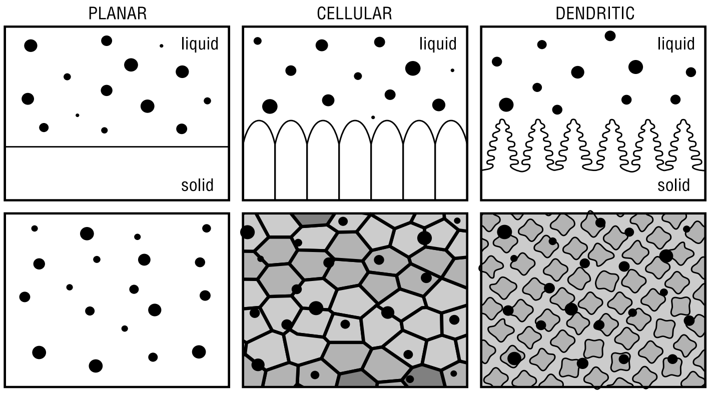
The photos show columnar (top) and equiaxed (bottom) structures of an alloy that is 97% aluminum and 3% copper, grown on Earth without (top) and with (bottom) nuclei in the melt.

This experiment will study the transition from columnar growth to equiaxed growth in the convection-free conditions available in the microgravity environment. Samples of aluminum-copper (AlCu) alloy will be solidified by controlled cooling in the AGHF. Two samples, with identical chemical composition, will be placed in a single cartridge so that one sample will be in an isothermal zone of the furnace and the other sample will be in a zone where the thermal gradient varies continuously. Two other cartridges with different quantities of nuclei in the samples will be processed under identical conditions during the mission. Thermocouples will be inserted into the crucible walls and in the long axis of the samples to measure thermal conditions.

The microstructures obtained in the samples will be compared to a theoretical model of the transition from columnar to equiaxed growth under diffusive conditions. This comparison will allow investigators to derive the influence of the natural convective motion of nuclei and equiaxed grains in Earth-based processing.



A special crucible of varying thermal conductivity and roughness, along with pulse marking, will be used to gather data on the way the curvature of the solid/liquid interface affects the growth of concentrated ternary compounds.



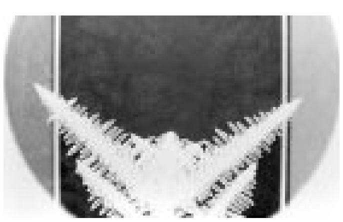
For interfaces having cellular or dendritic patterns, the local conditions that govern the interaction between a particle and the solid portion of the sample depend on the random point of contact between the particle and the microstructure. These drawings show the position of the particles relative to the solidification pattern in the view from the side (top) and the view from above (bottom).

Interactive Response of Advancing Phase Boundaries to Particles

Principal Investigator: Ulrike Hecht, Aachen Center for Solidification in Space (ACCESS) e.V., Aachen, Germany

Co-Investigators: Dr. Jochen Laakmann and Dr. Stephan Rex, ACCESS e.V., Aachen, Germany

Many natural and artificial composite structures offer unique properties that cannot be obtained with a single material. Particle-reinforced metal-matrix composites are such artificial structures. These alloys can be produced by dry processes that involve blending and pressing powders or by liquid processes that involve dispersal of



This photomicrograph from an experiment flown on the Second United States Microgravity Payload mission shows dendritic growth occurring during rapid cooling.

particles into a liquid base and solidification of the resulting material. The use of liquid processes can be much less expensive, but the mechanisms that govern the distribution of the particles are not understood fully.

During solidification, a band of solidifying liquid only a few atoms thick, known as the solidification interface, forms between the solid and the liquid portions of the sample. As the interface approaches so close that it almost touches the particle, forces begin to act between the atoms of the solid matrix and the atoms of the particle. If these forces are repulsive in nature, the particle can be "pushed" ahead of the interface into the last material to be solidified, eliminating the benefits that could have been obtained from a more even dispersion. By changing processing conditions, repulsive forces may not be sufficient to overcome inertia, allowing the particle to be engulfed readily into the solidifying material. Whether a particle is repulsed or is readily engulfed depends on the velocity of the solidification interface, the local temperature, and the solute concentration. Particle behavior, however, is extremely sensitive to fluid flows. Experiments in microgravity where heat and solute transport are predominately diffusive will allow for better investigation of the mechanism of particle incorporation.

This experiment investigates the effects of solidification conditions on the distribution of particles in the solid. It focuses on the different morphological patterns (the shape of the structures that form during solidification, which range from tiny finger-like cells to tree-like dendrites) of the solidification interface, on how the evolution of these structures is affected by the particles, and on how the distribution of the particles is affected by the morphology. Understanding the fundamental mechanisms of interaction between particles and the solidification interface will allow for verification of, or improvements to, theoretical models. This is essential for the development of materials with a particle distribution adapted to the specific use of the material and for the design of new and better industrial processes.

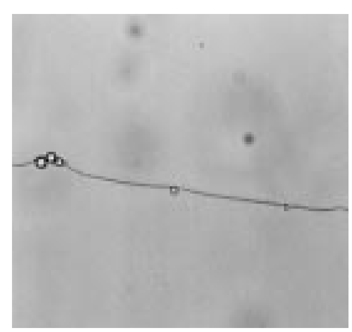
Particle Engulfment and Pushing by Solidifying Interfaces

Principal Investigator: Dr. Doru Stefanescu, University of Alabama, Tuscaloosa, Alabama

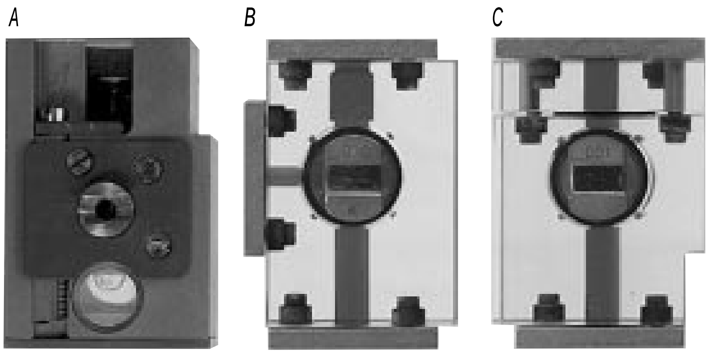
Co-Investigators: Dr. Peter Curreri and Dr. Shubayu Sen, NASA/Marshall Space Flight Center, Huntsville, Alabama; Dr. Brij Drindaw and Frank Juretzko, University of Alabama, Tuscaloosa, Alabama

A key issue in the fabrication of particulate metal-matrix composites by melt processing techniques is the need to achieve a uniform spacing of the reinforcing particles in the metal. This investigation studies the physics associated with the behavior of particles encountering a moving solidification interface. The experiment is designed to enhance the understanding of the physics associated with the solidification of liquid metals containing ceramic particles and to investigate the aspects of processing metal-matrix composites in microgravity, which may provide vital information to help improve such processing on Earth.

Samples of pure aluminum reinforced with zirconia particles will be processed in the AGHF using directional solidification. In a parallel ground-based effort, a transparent organic material (succinonitrile), which contains polystyrene particles, is used to visualize the experiment. The solidification behavior of the transparent sample is similar to that of metals, allowing investigators to observe the interaction of a particle at the solid/liquid interface as it occurs. Postflight examination of the samples will allow scientists to determine how fast the solid/liquid interface must move to engulf the particles instead of pushing them ahead of the interface. These data will be compared with similar studies on the ground to validate a theoretical model of the process.



This photograph shows a spherical particle being engulfed by a planar succinonitrile solid/liquid interface. The interface is moving downward. Note the concave interface curvature mismatch (caused by thermal conductivity) between the particle and the matrix.



The APCF is the first facility in which protein crystals can be grown by three techniques: (A) hanging drop method (B) free interface diffusion (C) dialysis

Advanced Protein Crystallization Facility (APCF), ESA

Conditions on Earth limit the size and quality of many protein crystals, but the microgravity environment of space is expected to allow the growth of larger, more highly ordered crystals. The APCF is the first facility to use three methods of protein crystal growth: liquid/liquid diffusion, or free interface diffusion, in which a protein solution and a salt solution are separated by a buffer and are allowed to flow together slowly once the Shuttle is in orbit; dialysis, with protein and salt solutions separated by a membrane; and vapor diffusion, or the hanging drop method, where crystals form inside a drop of protein solution as solvent from the drop diffuses to a reservoir.

Upon reaching orbit, the crew activates the unit, monitors the facility as it operates, and deactivates the equipment shortly before re-entry. Video images will be made of crystals as they form. After the mission, the images will allow investigators to study the history of crystal development in microgravity. Scientists are interested particularly in why and how crystals begin formation. When the crystals return from space, they will be analyzed, using precision X-ray beams (synchrotron radiation, whenever available), sophisticated detectors, and data-processing equipment to determine the internal arrangement of their atoms. As X-rays diffract off the atoms of the crystals, a computer will map each atom's position. This process is possible only with highly ordered and relatively large crystals. With these maps, scientists may be able to expand our understanding of biological processes at the molecular level, which could lead to applications in medicine and agriculture.

The APCF has 2 units, each of which has 48 crystallization reactors. European investigators will share one unit, while Dr. Alexander McPherson (an American Principal Investigator) will be in charge of the other.

Crystallization of EGFR-EGF

Principal Investigator:
Dr. Christian Betzel, European Molecular Biology Laboratory, Hamburg, Germany

The receptor for the epidermal growth factor (EGF) is increasing in its importance as a prognostic factor for a series of human malignancies. Knowledge of the three-dimensional structure of this receptor would open the possibility of tailoring appropriate drugs for the treatment of numerous types of tumors.

Crystallization of Crustacyanin Subunits

Principal Investigator: Dr. Naomi Chayen, Imperial College, London, United Kingdom

Crustacyanin is a member of the lipocalin family of proteins, which binds to certain pigments that are widely distributed in plants and animals. Knowledge of the structure of the lipocalins will enable scientists to engineer these proteins to produce carriers that will bind more strongly to pigments that have anti-cancer properties.

Crystallization of Engineered 5S rRNA Molecules

Principal Investigator:
Dr. Volker Erdmann, Free University of Berlin, Germany

The ribonucleic acid (RNA) 5S rRNA interacts in the ribosomes with a number of proteins and is essential for the biological activity of the ribosomes. This experiment will be performed with intact and biologically active RNA molecules and will enlarge the scope of knowledge on the effects of microgravity on the crystallization of biological macromolecules.

Crystallization of Thermus Thermophilus AspRS

Principal Investigator:
Dr. Richard Giegé, Centre National de la Recherche Scientifique (CNRS), Strasbourg, France

Ground-based investigators have crystallized successfully two protein-tRNA complexes [one, aspartyl-tRNA synthetase (AspRS), to an unmodified $tRNA^{Asp}$ transcript and one to the native $tRNA^{Asp}$]. The crystal quality of the complex with the transcript, however, is inferior to that of the complex with the natural rRNA. On the LMS mission, researchers want to grow these crystals in dialysis cells to obtain higher resolution X-ray data.

Monitoring of Lysozyme Protein Crystal Growth in Microgravity via a Mach-Zehnder Interferometer and Comparison with Earth Control Data

Principal Investigator:
Dr. John Helliwell, University of Manchester, United Kingdom

Essentially perfect lysozyme crystals grown on the Spacehab-1 and IML-2 missions had a three-fold reduction in mosaicity over Earth-grown controls. Investigators want to determine the optimum duration of a microgravity mission for protein crystallization.

Crystallization of the Nucleosome Core Particle in Space

Principal Investigator:
Dr. Timothy Richmond, ETH Zürich, Switzerland

The nucleosome core particle is the greater part of the nucleosome, the fundamental repeating unit of eukaryotic chromatin (the complex forming the major portion of the nuclear material in cells that have a definite nucleus). On LMS, scientists hope to obtain crystals with low mosaicities that will allow data collection to diffraction spacings beyond 3 Angstroms.

Enhanced Resolution Through Improved Crystal Quality in the Crystal Structure Analysis of Photosystem I

Principal Investigator:
Dr. Wolf Schubert, Free University of Berlin, Germany

Protein complexes Photosystem I and Photosystem II are responsible for the primary conversion of visible light into chemical energy in water-oxidizing photosynthesis. The objective of this experiment is to elucidate the complete arrangement of chlorophyll molecules, which perform this conversion process in the most efficient way.

Mechanism of Membrane Protein Crystal Growth: Bacteriorhodopsin – Mixed Micelle Packing at the Consolution Boundary, Stabilized in Microgravity

Principal Investigator:
Dr. Gottfried Wagner, University of Giessen, Germany

Bacteriorhodopsin converts light energy to voltages in the membrane of photoenergetic microorganisms that are chemically and genetically distinct from bacteria and higher living organisms. Resolution of the three-dimensional structure of this protein will help scientists understand the mechanisms used to convert light energy to energy for growth.

Crystallization in a Microgravity Environment on CcdB, a Protein Involved in the Control of Cell Death

Principal Investigator:
Dr. Lode Wyns, Free University of Brussels, Belgium

Clarification of the structure and mode of action of the CcdB protein may lead to the design of new antibiotics and anti-tumoral drugs. Specifically, crystal quality needs to be improved, and researchers want to crystalize three specific serine to cysteine mutants (Ser74Cys, Ser84Cys, and double mutant Ser74Cys Gly77Cys), which have not produced crystals large enough for data collection.

Crystallization of Sulfolobus Solfataricus Alcohol Dehydrogenase

Principal Investigator:
Dr. Adriana Zagari, University of Napoli, Italy

Alcohol dehydrogenase (ADG), an enzyme that occurs in large amounts in the livers of mammals, plays an important role in several physiological functions, including the breakdown of alcohol. Mammalian ADH is unstable at high temperatures or in the presence of organic solvents, properties that limit its biotechnological application to the synthesis of organic compounds. ADH from *Sulfolobus solfataricus*, a bacterium that thrives at high temperatures, has greater thermal stability, however, and is scarcely affected by the presence of organic solvents. Given these properties, the enzyme is a good candidate for industrial applications.

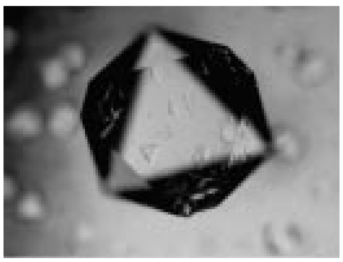
Growth of Lysozyme Crystals at Low Nucleation Density

Principal Investigator:
Dr. Juan Garcia-Ruiz, University of Granada, Spain

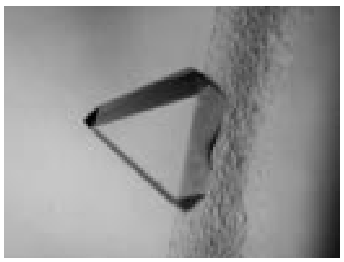
This experiment will employ a new approach to lysozyme crystallization, using a high concentration of both salt and protein solutions to provoke an amorphous precipitation at the beginning of the experiment and then to permit the system to self-organize. The objective of this investigation is to obtain information for evaluating the usefulness of ground-based experiments in predicting growth behavior under microgravity conditions and to test the degree of realism of computer simulations of one-dimensional cells developed in ground-based laboratories.

A

B



C



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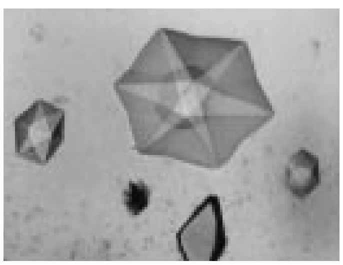
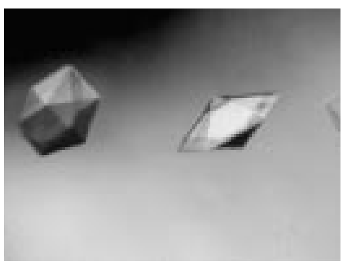


E



F

Above are photos of crystals of proteins and viruses grown by liquid/liquid diffusion during the IML-2 mission. Both rhombohedral and hexagonal crystals of the plant seed protein canavalin are pictured in photos A and B. The rhombohedral crystals are up to 1 mm on an edge, as are the lengths of the hexagonal prisms, which are characterized by a deep occlusion along the central axis. This cusp is not seen in crystals grown in a conventional laboratory. Photos C and D picture two examples of the unusually large cubic crystals of satellite tobacco mosaic virus, which are more than 30 times the size of similar crystals grown on Earth. These crystals (D) can be seen nucleated from the surface of the quartz cell. The background of microcrystals seen in photo C is believed to have appeared after re-entry from space. Photos E and F show crystals of turnip yellow mosaic virus that display the unique, multifaceted forms that have been observed only in these microgravity-grown crystals. The magnification of all photos is 40X.

Advanced Protein Crystallization Facility on the Life and Microgravity Sciences Mission

Principal Investigator:
Dr. Alexander McPherson,
University of California,
Riverside, California

This experiment will grow a variety of protein and virus crystals in the APCF. The growth technique will be liquid/liquid diffusion with relatively large macromolecule solution volumes of 200 to 500 microliters, and a range of precipitant concentrations, precipitant varieties, pHs, and effector components will be investigated.

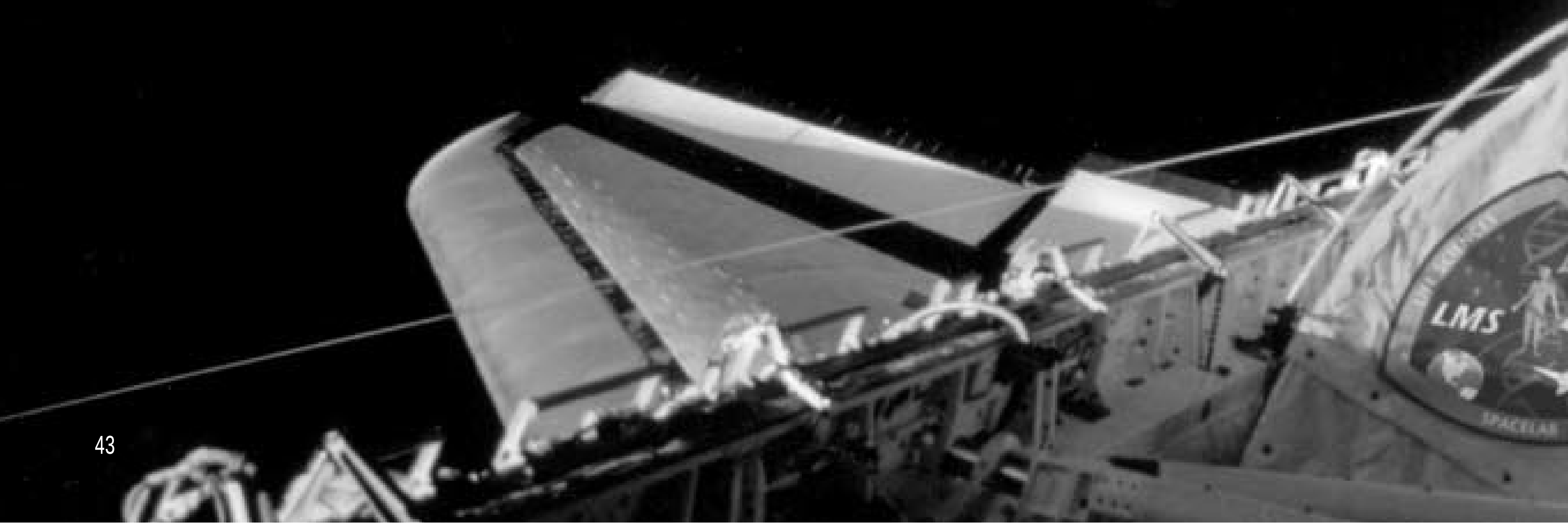
While protein samples will be included among the crystallization trials, the emphasis will be on viruses having diameters of either 170 Å or 280 Å. These macromolecular assemblies were chosen because their large size results in a very low rate of diffusion. Because the effects of microgravity are likely to be most pronounced for particles of very low diffusivity (mobility), researchers believe that virus crystals may exhibit the most dramatic differences when compared with corresponding crystals grown in Earth-based laboratories.

Specific virus samples will include Satellite Panicum Mosaic Virus and Turnip Yellow Mosaic Virus, both of which have been investigated on previous missions (Spacehab and IML-2). New viruses to be studied include Desmodium Yellow Mottle Virus, Tomato Virus, and Panicum Mosaic Virus, all of which have diameters of 280 Å.

The investigation on LMS provides a particularly valuable opportunity because a large variety of experiments covering a broad range of samples and conditions can be evaluated simultaneously. In addition, 12 of the 48 crystallization reactors will be recorded at time intervals by video microscopy, allowing investigators to define the initiation of crystal growth, the crystal growth rates, and the development of morphology. Also, they will be able to document anomalous events or acceleration fluctuations and to record the spatial and size distribution of crystals within the growth cells. From these observations, a number of conclusions regarding the mechanisms and kinetics of crystal growth in microgravity may be deduced. These experiments will contribute to a better understanding of macromolecular crystal growth on Earth and to our ability to define that process in conventional laboratories, possibly accelerating important advances in biotechnology, medicine, agriculture, and industry.

The record of scientific achievement during more than a decade of research aboard the Space Shuttle/Spacelab is remarkable. The space laboratory has been a successful research facility for many scientific disciplines, providing opportunities for scientists to gather data that have opened our eyes to new lines of inquiry, unexpected results, and intriguing problems that require further experiments and observations. Many questions that have been raised across all fields of scientific research are not answered easily and require repeated experimentation in the microgravity environment. While no single experiment from any mission will provide the ultimate answer to these questions, the information gathered will be combined with data obtained on previous and future missions to develop solutions to many of the problems facing us on Earth and in space.

The Life and Microgravity Spacelab mission represents the attempt being made throughout the world's space community to continue the exploration of space through the establishment of critical biomedical foundations and quality microgravity science technology. With Columbia's successful launch, 16-day on-orbit operation, and landing, LMS will bring the scientific community one step closer to answering the questions posed by both life science and microgravity science disciplines. This successful gathering of scientific information, which has characterized the space program from its inception, will continue to ensure a vigorous worldwide space program and to enhance the quality of life on Earth as we move into the next century.



LMS MISSION MANAGEMENT

Management and Development

NASA Headquarters, Washington, D.C., United States

Program Manager: David Jarrett

Life Sciences Instrument Program Manager: Angie Jackman

Program Scientist: Dr. Victor Schneider

Microgravity Program Scientist: Dr. Bradley Carpenter

NASA Marshall Space Flight Center, Huntsville, Alabama

Mission Manager: Mark Boudreaux

Assistant Mission Manager: Kimball Ibrahim

Mission Scientist: Dr. James Patton Downey

Mission Scientist Support: Rick McConnell, USRA

Chief Engineer: Steve Newton

Payload Operations Director: Barbara Cobb

Spacelab Integration Manager: Chris Crumbly

Training Manager: George Norris

Operations Controller: Kim Krome

Data Management Coordinator: Annie Johnson

Payload Activity Planner: Karla Kochevar

Safety and Mission Assurance: Mike Kim

MSFC/KSC Resident Office: Emmett Crooks

NASA Johnson Space Center, Houston, Texas

Flight Manager: John D. Holt

Flight Director: John Shannon

Payload Integration Manager: Ed Jung

NASA Kennedy Space Center, Cape Canaveral, Florida, United States

Launch Site Support Manager: Daniel Shultz

Teledyne Brown Engineering (TBE) Project Office, Payload Mission Integration Contractor, Huntsville, Alabama

Project Manager: Scott Copeland

Lead Systems Engineer: Mike Phillips

Lead Operations Engineer: John Bartlett

Mission-Peculiar Equipment Lead Engineer: Jeff Smith

Experiment Integration Engineers: Jim Sykes, Bob Heinisch, Dennis Lang

Safety Manager: Lloyd Silva

Safety Engineer: Kathryn Van Peursem

McDonnell Douglas, Spacelab Integration Contractor, Huntsville, Alabama

Mission Integration Manager: R.L. Holland

Project Specialist: Beth Lasater

Experiment Management

LIFE SCIENCES

Human Life Science — JSC Project, NASA/JSC, Houston, Texas

Project Scientist: Dr. Mel Buderer

Project Manager: Ladonna Miller

Project Coordinators: Darren Lajaunie and Lisa Swanson, Lockheed-Martin, Webster, Texas

Bedrest Study — Ames Research Center, Moffett Field, California

Project Manager: Dee O'Hara

Project Scientist: Dr. Sara Arnaud

SPACE BIOLOGY

Animal Enclosure Module (AEM), NASA/AMES Research Center, Moffett Field, California

Project Manager/Payload Element Developer: Dr. Randall Berthold

Project Scientist: Dr. Charles Winget NASA/ARC, Moffett Field, California

Plant Growth Facility (PGF), NASA/Kennedy Space Center, Cape Canaveral, Florida

Project Manager: Cindy Martin

Payload Element Developer: Debbie Vordermark, Bionetics Corp, KSC, Florida

Space Tissue Loss Module — Configuration B (STL-B)

Project Manager: Capt. Craig Lamb, United States Air Force at NASA/JSC, Houston, Texas

Project Scientist: Dr. Charles Winget, NASA/ARC, Moffett Field, California

Payload Element Developer: Alex Pranger, Walter Reed Army Institute of Research, Washington, D.C.

MICROGRAVITY SCIENCE

Bubble, Drop, and Particle Unit (BDPU)

Project Manager/Payload Element Developer: Pasquale DiPalermo, ESA/ESTEC, Noordwijk, The Netherlands

Science Coordinator (European Experiments): Dr. Philippe Géoris, Free University of Brussels, Belgium

Project Scientist (American Experiments): Myron Hill, NASA/Lewis Research Center, Cleveland, Ohio

Accelerometers

Microgravity Measurement Assembly (MMA)

Payload Manager: Dr. Maurizio Nati, ESA/ESTEC, Noordwijk, the Netherlands

Principal Investigator Microgravity Services, NASA/Lewis Research Center, Cleveland, Ohio

Manager: Richard DeLombard, NASA/Lewis Research Center, Cleveland, Ohio

Project Scientist: Dr. Roshanak Hakimzadeh, NASA/Lewis Research Center, Cleveland, Ohio

Space Acceleration Measurement System (SAMS)

Project Manager: Ron Sicker, NASA/Lewis Research Center, Cleveland, Ohio

Orbital Acceleration Research Experiment (OARE)

Project Manager: William Wagar, NASA Lewis Research Center, Cleveland, Ohio

Advanced Gradient Heating Facility (AGHF)

Project Manager/Payload Element Developer: Claus Alfermann, ESA/ESTEC, Noordwijk, The Netherlands

Project Manager (American Experiments): Fred Reeves, NASA/MSFC, Huntsville, Alabama

Project Scientist (European Experiments): Dr. Jurgen Ströde, ESA/ESTEC, Noordwijk, The Netherlands

Project Scientist (American Experiments): Dr. Peter Curreri, NASA/MSFC, Huntsville, Alabama

Advanced Protein Crystallization Facility (APCF)

Project Manager/Payload Element Developer: Klaus Fuhrmann, ESA/ESTEC, Noordwijk, The Netherlands

Project Manager (American Experiments): Ron King, NASA/MSFC, Huntsville, Alabama

Project Scientist (European Experiments): Dr. Gottfried Wagner. Justus-Liebig University, Giessen, Germany

Project Scientist (American Experiments): Bill Witherow, NASA/MSFC, Huntsville, Alabama

GLOSSARY OF ACRONYMS

ACCESS	Aachen Center for Solidification in Space
AEM	Animal Enclosure Module
AGHF	Advanced Gradient Heating Facility
ALFE	Astronaut Lung Function Experiment
APCF	Advanced Protein Crystallization Facility
ASI	Italian Space Agency/Agenzia Spaziale Italiana
BDPU	Bubble, Drop, and Particle Unit
CAPCOM	Capsule Communicator
CEA	Commissariat l'Énergie Atomique
CNES	French Space Agency/Centre National d'Etudes Spatiales
CNRS	French National Scientific Research Center/Centre National de la Recherche Scientifique
COIS	Canal and Otolith Integration Studies
CSA	Canadian Space Agency/Agence Spatiale Canadienne
CT	Computed Tomography
D-2	The Second German Spacelab mission
DARA	German Space Agency/Deutsche Agentur für Raumfahrtangelegenheiten GmbH
DEXA	Dual Photon X-ray Absorptiometry
DLR	German Aerospace Research Establishment/Deutsche Forschungsanstalt für Luft-und Raumfahrt e.V.
DLW	Doubly Labeled Water
ECG	Electrocardiogram
EEG	Electroencephalograph
EMG	Electromyogram
ESA	European Space Agency/Agence Spatiale Européenne
ESTEC	European Space Research and Technology Center
GASMAP	Gas Analyzer System for Metabolic Analysis Physiology
HIF	Human Interface
IML-1	First International Microgravity Laboratory
IML-2	Second International Microgravity Laboratory
IWG	Investigator Working Group
JSC	Johnson Space Center
KSC	Kennedy Space Center
LCD	Liquid Crystal Display
LeRC	Lewis Research Center
LMS	Life and Microgravity Spacelab
LSLE	Life Sciences Laboratory Equipment
MARS	Microgravity Advanced Research and Support center
MMA	Microgravity Measurement Assembly
MRI	Magnetic Resonance Imaging
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OARE	Orbital Acceleration Research Experiment
OKN	Optokinetic Nystagmus
PAWS	Performance Assessment Workstation
PEMS	Percutaneous Electrical Muscle Stimulation
PGF	Plant Growth Facility
PI	Principal Investigator
POCC	Payload Operations Control Center
REM	Rapid Eye Movement
SACS	Human Sleep, Circadian Rhythms, and Performance in Space
SAMS	Space Acceleration Measurement System
SL	Spacelab
SLAMMD	Space Linear Acceleration Mass Measurement Device
SLS-1	Spacelab Life Sciences 1
SLS-2	Spacelab Life Sciences 2
SMCI	Supramaximal Current Intensity
STL-B	Space Tissue Loss – Configuration B
STS	Space Transportation System
TRE	Torso Rotation Experiment
TVD	Torque Velocity Dynamometer
VHM	Voluntary Head Movements

This brochure was developed by a team of writers at Essex Corporation through a contract with Teledyne Brown Engineering under the auspices of the Payload Projects Office, NASA/Marshall Space Flight Center, Huntsville, Alabama.

Project Lead: Sandra Murphree

Additional information about the LMS mission
is available on the World Wide Web at the following address:

http://liftoff.msfc.nasa.gov/spacelab/lms